2024 Update to:

Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing (Version 3.0)

Underwater and In-Air Criteria for Onset of Auditory Injury and Temporary Threshold Shifts

Office of Protected Resources
National Marine Fisheries Service
Silver Spring, MD 20910

U.S. Department of Commerce
National Oceanic and Atmospheric Administration
National Marine Fisheries Service

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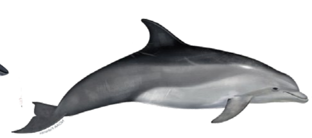

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ABBREVIATIONS, ACRONYMS, AND SYMBOLS

a	Low-frequency exponent
ABR	Auditory Brainstem Response
AEP	Auditory Evoked Potentials
ANSI	American National Standards Institute
AUD INJ	Auditory Injury
b	High-frequency exponent
C	Weighting function gain (dB)
dB	Decibel
$E(f)$	Auditory exposure function
E_0	Exposure Threshold
EEH	Equal Energy Hypothesis
EQL	Equal Loudness
ES	Executive Summary
ESA	Endangered Species Act
f_0	Best hearing (kHz)
f_1	Low-frequency cutoff (kHz)
f_2	High-frequency cutoff (kHz)
h	hour
HF	High-frequency cetacean
Hz	Hertz
in^3	Cubic inches
ISO	International Organization for Standardization
IQG	Information Quality Guidelines
K	Exposure function gain (dB)
kHz	Kilohertz
LF	Low-frequency cetacean
$L_{0\text{-pk}}$	Peak sound pressure level
$L_{0\text{-pk,flat}}$	Unweighted peak sound pressure level
$L_{\text{E,24h}}$	Sound exposure level, cumulative 24h
MF	Mid-frequency
min	Minutes
MMC	Marine Mammal Commission
MMPA	Marine Mammal Protection Act
MSA	Magnuson-Stevens Fishery Conservation and Management Act
m	meter
ms	Milliseconds
NIHL	Noise-induced Hearing Loss
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NSF	National Science Foundation
OA	Otariids in air
OMB	Office of Management and Budget
OPR	Office of Protected Resources
OSHA	Occupational Safety and Health Administration
OW	Otariid pinnipeds in water
PA	Phocids in air
Pa	Pascals
PK SPL	peak sound pressure level
PTS	Permanent Threshold Shift
PW	Phocid pinnipeds in water
R^2	Goodness of fit
RMS SPL	Root-Mean-Square sound pressure level
SEL	Sound exposure level
SEL_{24h}	Cumulative sound exposure level over 24-h
SOST	Subcommittee on Ocean Science and Technology
SPL	Sound Pressure Level
s_0	Slope (dB/decade)
TS	Threshold Shift
TTS	Temporary Threshold Shift
μPa	Micropascal
μPa^2s	Micropascal squared second
USFWS	U.S. Fish and Wildlife Service
VHF	Very High-frequency cetacean
$W(f)$	Auditory weighting function

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EXECUTIVE SUMMARY

This document provides technical updates and replaces the NMFS 2018 Revised Technical Guidance and is to be used for assessing the effects of underwater and in-air anthropogenic (human-made) sound on the hearing of marine mammal species under the jurisdiction of the National Marine Fisheries Service (NMFS). Specifically, it identifies the received levels and auditory weighting functions, or criteria, at which individual marine mammals are predicted to experience changes in their hearing sensitivity (either temporary or permanent) for acute (≤24 hours), incidental exposure to underwater or in-air anthropogenic sound sources based on updated information. This Updated Technical Guidance may be used by NMFS analysts/managers and other relevant action proponents/stakeholders, including other federal agencies, when seeking to determine whether and how their activities are expected to result in potential impacts to marine mammal hearing via acoustic exposure. This document outlines the development of NMFS's criteria and describes how they will be updated in the future.

NMFS has compiled, interpreted, and synthesized the scientific literature, including a Technical Report by Dr. James J. Finneran (U.S. Navy-Naval Information Warfare Center Pacific (NIWC-PAC)) (Finneran 2024; Appendix A of this Updated Technical Guidance), to produce criteria for onset of temporary threshold shifts (TTS) and auditory injury (AUD INJ), which includes, but is not limited to, permanent threshold shifts (PTS)) (Table ES2) based on updated information. This document includes a protocol for the formation of marine mammal hearing groups (low- (LF), high- (HF), and very high- (VHF) frequency cetaceans, otariid (OW) and phocid (PW) pinnipeds in water, and otariid (OA) and phocid (PA) pinnipeds in air (Table ES1)), the derivation of marine mammal auditory weighting functions (Figures ES1 through ES3), and the estimation of AUD INJ onset criteria for impulsive (e.g., airguns, impact hammers, explosives) and non-impulsive (e.g., tactical sonar, vibratory hammers, drills) sound sources. These criteria are presented using dual metrics of weighted cumulative sound exposure level (SEL_{24h}) and peak sound pressure level (PK SPL) for impulsive sounds and weighted SEL_{24h} for non-impulsive sounds.

The Updated Technical Guidance's criteria reflect the current state of scientific knowledge regarding the characteristics of sound that have the potential to impact marine mammal hearing sensitivity. NMFS recognizes that the implementation of marine mammal weighting functions and the weighted SEL_{24h} criteria may extend beyond the capabilities of some action proponents. Thus, NMFS has developed an optional, alternative tool for those who cannot fully incorporate these factors into their own analyses (See Updated Technical Guidance's companion optional User Spreadsheet tool[1]).

These criteria do not represent the entirety of a comprehensive analysis of the effects of a proposed action, but rather serve as one tool (along with, e.g., behavioral disturbance criteria, auditory masking assessments, evaluations to help understand the ultimate effects of any particular type of impact on an individual's fitness, population assessments, etc.) to help evaluate the effects of a proposed action and make the relevant findings required by NOAA's various statutes. The Updated Technical Guidance may inform decisions related to mitigation and monitoring requirements, but it does not mandate any specific mitigation measures. The Updated Technical Guidance does not address or change NMFS's application of these criteria in the regulatory context under applicable statutes and does not create or confer any rights for or on any person, or operate to bind the public. It only updates NMFS's criteria based on the most recent science.

Independent peer review was required prior to broad public dissemination by the Federal Government. Details of the peer review, associated with the Updated Technical Guidance, are within this document (Appendix C).

[1] https://www.fisheries.noaa.gov/national/marine-mammal-protection/marine-mammal-acoustic-technical-guidance.

SUMMARY OF TECHNICAL ASPECTS

This document is organized so that the most pertinent information can be found easily in the main body. Additional details are provided in the appendices. Section I introduces the document. NMFS's criteria for onset of AUD INJ for marine mammals exposed to underwater or in-air sounds are presented in Section II. NMFS's plan for periodically updating criteria is presented in Section III. More details on the development of criteria, the peer review and public comment processes, research recommendations, and a glossary of acoustic terms are found in the appendices.

The following Tables and Figures summarize the three main aspects of the Updated Technical Guidance: 1) Marine mammal hearing groups (Table ES1); 2) Marine mammal auditory weighting functions (Figures ES1 through ES3; Table ES2); and AUD INJ onset criteria (Table ES3).

Table ES1: Marine mammal hearing groups.

Hearing Group^	Generalized Hearing Range*
UNDERWATER	
Low-frequency (LF) cetaceans (baleen whales)	7 Hz to 36+ kHz
High-frequency (HF) cetaceans (dolphins, toothed whales, beaked whales, bottlenose whales)	150 Hz to 160 kHz
Very High-frequency (VHF) cetaceans (true porpoises, *Kogia*, river dolphins, cephalorhynchid, *Lagenorhynchus cruciger* & *L. australis*)	200 Hz to 165 kHz
Phocid pinnipeds (PW) (true seals)	40 Hz to 90 kHz
Otariid pinnipeds (OW) (sea lions and fur seals)	60 Hz to 68 kHz
IN-AIR	
Phocid pinnipeds (PA) (true seals)	42 Hz to 52 kHz
Otariid pinnipeds (OA) (sea lions and fur seals)	90 Hz to 40 kHz

^ Southall et al. 2019 indicates that as more data become available there may be separate hearing group designations for Very Low-Frequency cetaceans (blue, fin, right, and bowhead whales) and Mid-Frequency cetaceans (sperm, killer, and beaked whales). However, at this point, all baleen whales are part of the LF cetacean hearing group, and sperm, killer, and beaked whales are part of the HF cetacean hearing group. Additionally, recent data indicates that as more data become available for Monachinae seals, separate hearing group designations may be appropriate for the two phocid subfamilies (Ruscher et al. 2021; Sills et al. 2021).

* Represents the generalized hearing range for the entire group as a composite (i.e., all species within the group), where individual species' hearing ranges may not be as broad. Generalized hearing range chosen based on ~65 dB threshold from composite audiogram, previous analysis in NMFS 2018, and/or data from Southall et al. 2007; Southall et al. 2019. Additionally, animals are able to detect very loud sounds above and below that "generalized" hearing range.

+ NMFS is aware that the National Marine Mammal Foundation successfully collected preliminary hearing data on two minke whales during their third field season (2023) in Norway. These data have implications for not only the generalized hearing range for low-frequency cetaceans but also on their weighting function. However, at this time, no official results have been published. Furthermore, a fourth field season (2024) is proposed, where more data will likely be collected. Thus, it is premature for us to propose any changes to our current Updated Technical Guidance. However, mysticete hearing data is identified as a special circumstance that could merit re-evaluating the acoustic criteria in this document. Therefore, we anticipate that once the data from both field seasons are published, it will likely necessitate updating this document (i.e., likely after the data gathered in the summer 2024 field season and associated analysis are published).

Table ES2: Summary of auditory weighting and exposure function parameters.0

Hearing Group	a	b	f_1 (kHz)	f_2 (kHz)	C (dB)	K (dB)
UNDERWATER						
Low-frequency (LF) cetaceans	0.99	5	0.168	26.6	0.12	177
High-frequency (HF) cetaceans	1.55	5	1.73	129	0.32	181
Very High-frequency (VHF) cetaceans	2.23	5	5.93	186	0.91	160
Phocid pinnipeds (PW)	1.63	5	0.81	68.3	0.29	175
Otariid pinnipeds (OW)	1.58	5	2.53	43.8	1.37	178
IN-AIR						
Phocid pinnipeds (PA)	2.05	5	0.74	24.4	0.83	133
Otariid pinnipeds (OA)	1.35	5	1.75	32.5	1.18	156

* Equations associated with Updated Technical Guidance's auditory weighting (*W(f)*) and exposure functions (*E(f)*):

$$W(f) = C + 10\log_{10}\left\{\frac{(f/f_1)^{2a}}{[1+(f/f_1)^2]^a\,[1+(f/f_2)^2]^b}\right\} \quad \text{dB}$$

$$E(f) = K - 10\log_{10}\left\{\frac{(f/f_1)^{2a}}{[1+(f/f_1)^2]^a\,[1+(f/f_2)^2]^b}\right\} \quad \text{dB}$$

Table ES3: Summary of Marine Mammal AUD INJ onset criteria.

	AUD INJ Onset Criteria* (Received Level) PLEASE SEE TABLE NOTES TO FULLY UNDERSTAND SYMBOL MEANING	
Hearing Group	**Impulsive**	**Non-impulsive**
UNDERWATER		
Low-Frequency (LF) Cetaceans	*Cell 1* $L_{p,\text{0-pk,flat}}$: 222 dB $L_{E,p,\text{ LF,24h}}$: 183 dB	*Cell 2* $L_{E,p,\text{ LF,24h}}$: 197 dB
High-Frequency (HF) Cetaceans	*Cell 3* $L_{p,\text{0-pk,flat}}$: 230 dB $L_{E,p,\text{ HF,24h}}$: 193 dB	*Cell 4* $L_{E,p,\text{ HF,24h}}$: 201 dB
Very High-Frequency (VHF) Cetaceans	*Cell 5* $L_{p,\text{0-pk,flat}}$: 202 dB $L_{E,p,\text{VHF,24h}}$: 159 dB	*Cell 6* $L_{E,p,\text{ VHF,24h}}$: 181 dB
Phocid Pinnipeds (PW)	*Cell 7* $L_{p,\text{0-pk.flat}}$: 223 dB $L_{E,p,\text{PW,24h}}$: 183 dB	*Cell 8* $L_{E,p,\text{PW,24h}}$: 195 dB
Otariid Pinnipeds (OW)	*Cell 9* $L_{p,\text{0-pk,flat}}$: 230 dB $L_{E,p,\text{OW,24h}}$: 185 dB	*Cell 10* $L_{E,p,\text{OW,24h}}$: 199 dB
IN-AIR		
Phocid Pinnipeds (PA)	*Cell 11* $L_{p,\text{0-pk.flat}}$: 162 dB $L_{E,p,\text{PA,24h}}$: 140 dB	*Cell 12* $L_{E,p,\text{PA,24h}}$: 154 dB
Otariid Pinnipeds (OA)	*Cell 13* $L_{p,\text{0-pk,flat}}$: 177 dB $L_{E,p,\text{OA,24h}}$: 163 dB	*Cell 14* $L_{E,p,\text{OA,24h}}$: 177 dB

* Dual metric criteria for impulsive sounds: Use whichever criteria results in the larger isopleth for calculating AUD INJ onset. If a non-impulsive sound has the potential of exceeding the peak sound pressure level criteria associated with impulsive sounds, the PK SPL criteria are recommended for consideration for non-impulsive sources.

Note: Peak sound pressure level ($L_{p,\text{0-pk}}$) has a reference value of 1 µPa (underwater) and 20 µPa (in air), and weighted cumulative sound exposure level ($L_{E,p}$) has a reference value of 1 $\mu Pa^2 s$ (underwater) and 20 $\mu Pa^2 s$ (in air). In this Table, criteria are abbreviated to be more reflective of International Organization for Standardization standards (ISO 2017; ISO 2020). The subscript "flat" is being included to indicate peak sound pressure are flat weighted or unweighted within the generalized hearing range of marine mammals underwater (i.e., 7 Hz to 165 kHz) or in air (i.e., 42 Hz to 52 kHz). The subscript associated with cumulative sound exposure level criteria indicates the designated marine mammal auditory weighting function (LF, HF, and VHF cetaceans, and PW, OW, PA, and OA pinnipeds) and that the recommended accumulation period is 24 hours. The weighted cumulative sound exposure level criteria could be exceeded in a multitude of ways (i.e., varying exposure levels and durations, duty cycle). When possible, it is valuable for action proponents to indicate the conditions under which these criteria will be exceeded.

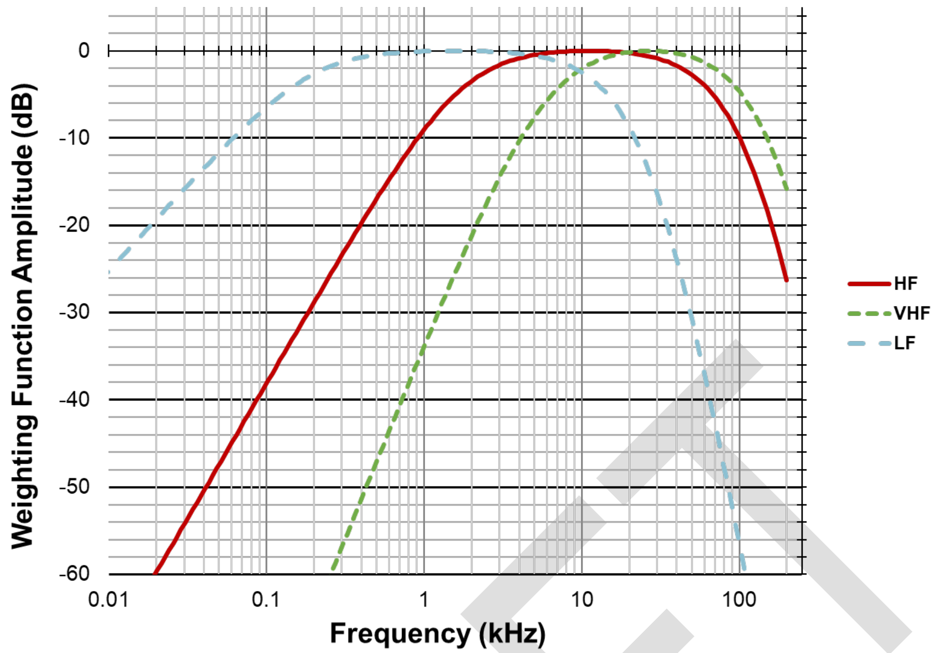

Figure ES1: **Auditory weighting functions for low-frequency (LF; blue dashed line), high-frequency (HF; red solid line), and very high-frequency (VHF; green dotted line) cetaceans.**

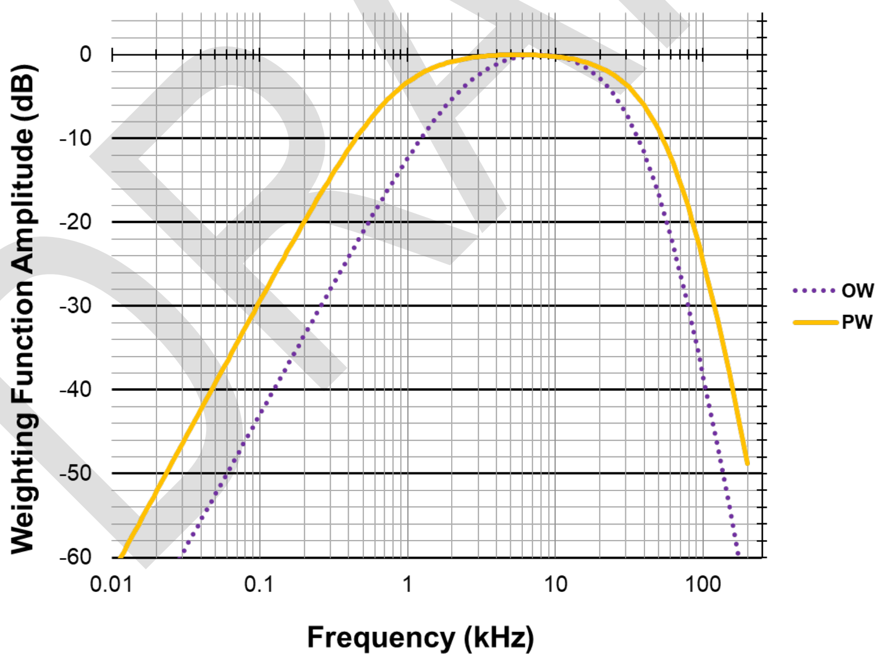

Figure ES2: **Underwater auditory weighting functions for otariid (OW; purple dotted line) and phocid (PW; orange solid line) pinnipeds.**

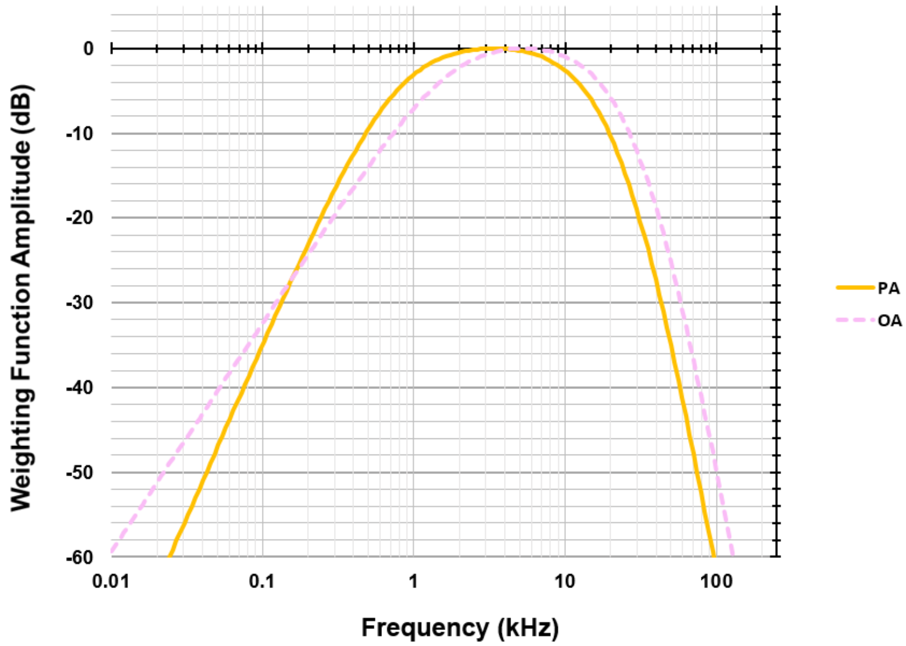

Figure ES3: **In-air auditory weighting functions for otariid (OA; dashed pink line) and phocid (PA; solid yellow line) pinnipeds.**

UPDATE TO: TECHNICAL GUIDANCE FOR ASSESSING THE EFFECTS OF ANTHROPOGENIC SOUND ON MARINE MAMMAL HEARING (VERSION 3.0)

UNDERWATER AND IN-AIR CRITERIA FOR ONSET OF AUDITORY INJURY AND TEMPORARY THRESHOLD SHIFTS

I. INTRODUCTION

This document provides Updated Technical Guidance[2] for assessing the effects of anthropogenic (human-made) sound on the hearing of marine mammal species under the jurisdiction[3] of the National Marine Fisheries Service (NMFS). Specifically, it identifies the received levels and auditory weighting functions, or criteria, at which individual marine mammals are predicted to experience changes in their hearing sensitivity for acute (≤24 hours), exposure to all underwater and in-air anthropogenic sound sources based on updated information, specifically onset of temporary threshold shifts (TTS) and auditory injury (AUD INJ).

For the purpose of this Updated Technical Guidance, TTS and AUD INJ, which includes, but is not limited to, PTS, are defined as follows:

- Temporary threshold shift (TTS): A temporary, reversible increase in the threshold of audibility at a specified frequency or portion of an individual's hearing range above a previously established reference level (ANSI 1995; Yost 2007). Based on data from cetacean TTS measurements (see Southall et al. 2019 for a review), a TTS of 6 dB is considered the minimum threshold shift clearly larger than any day-to-day or session-to-session variation in a subject's normal hearing ability (Schlundt et al. 2000; Finneran et al. 2000; Finneran et al. 2002).

- Auditory injury (AUD INJ): Damage to the inner ear that can result in destruction of tissue, such as the loss of cochlear neuron synapses or auditory neuropathy (Houser 2021; Finneran 2024). Auditory injury[4] may or may not result in a permanent threshold shift (PTS).

    - Permanent threshold shift (PTS): A permanent, irreversible increase in the threshold of audibility at a specified frequency or portion of an individual's

[2] The use of the Updated Technical Guidance is not mandatory; it does not create or confer any rights for or on any person, or operate to bind the public. An alternative approach that has undergone independent peer review may be proposed (by federal agencies or prospective action proponents) and used if case-specific information/data indicate that the alternative approach is likely to produce a more accurate estimate of auditory impact for the project being evaluated; and if NMFS determines the approach satisfies the requirements of the applicable statutes and regulations. This document replaces the previous iteration of NMFS 2018 Revised Technical Guidance (NMFS 2018).

[3] https://www.fisheries.noaa.gov/species-directory. This document does not pertain to marine mammal species under the U.S. Fish and Wildlife Service's (USFWS) jurisdiction (e.g., walrus, polar bears, manatees, dugongs, sea otters). However, since marine mammal audiogram data are limited, a decision was made to include all available datasets from in-water groups, including sirenian datasets (Gerstein et al. 1999; Mann et al. 2009), to derive composite audiogram parameters and threshold of best hearing for LF cetaceans (see Appendix A_1). Additionally, audiogram data from a single Pacific walrus (Kastelein et al. 2002a) and a single sea otter (Ghoul and Reichmuth 2014) were included in the derivation of the composite audiogram for OW pinnipeds and in-air hearing data from sea otters (Ghoul and Reichmuth 2014) and polar bears (Nachtigall et al. 2007; Owen and Bowles 2011) were used to derive the composite audiogram for the OA pinniped (in air) hearing group.

[4] In situations where destruction of auditory tissue has occurred in terrestrial mammals, threshold shifts were 30–50 dB measured 24 h after the exposure. There is no evidence that an exposure resulting in < 40 dB TTS measured a few minutes after exposure can produce AUD INJ. Therefore, an exposure producing 40 dB of TTS, measured a few minutes after exposure is used as an upper limit to prevent AUD INJ (i.e., it is assumed that exposures beyond those capable of causing 40 dB of TTS have the potential to result in AUD INJ, which may or may not result in PTS).

hearing range above a previously established reference level (ANSI 1995; Yost 2007). Available data from humans and other terrestrial mammals indicate that a 40 dB threshold shift approximates PTS onset (see Ward et al. 1958, 1959; Ward 1960; Kryter et al. 1966; Miller 1974; Ahroon et al. 1996; Henderson et al. 2008).

This Updated Technical Guidance is intended for use by NMFS analysts/managers and other relevant action proponents/stakeholders, including other federal agencies, when seeking to determine whether and how their activities are expected to result in impacts to marine mammal hearing via acoustic exposure. This document outlines NMFS's criteria, describing in detail criteria development (via Appendix A), and how they will be revised and updated in the future.

The criteria presented in this document do not represent the entirety of an effects analysis, but rather serve as one tool among others (e.g., behavioral impact criteria, auditory masking assessments, evaluations to help understand the effects of any particular type of impact on an individual's fitness, population assessments, etc.) to help evaluate the effects of a proposed action and make findings required by NOAA's various statutes. The Updated Technical Guidance may inform decisions related to mitigation and monitoring requirements, but it does not mandate any specific mitigation be required[5]. The Updated Technical Guidance does not address or change NMFS's application of these criteria in the regulatory context, under applicable statutes and does not create or confer any rights for or on any person, or operate to bind the public. It only updates NMFS's criteria based on the most recent science.

1.1 Criteria within the Context of an Effects Analysis

The Updated Technical Guidance's criteria do not represent the entirety of an effects analysis, but rather serve as one tool to help evaluate the effects of sound produced during a proposed action on marine mammals and help make findings required by NOAA's various statutes. In a regulatory context, NMFS uses criteria to help assess and quantify "take" and to conduct more comprehensive effects analyses under several statutes.

Specifically, the Updated Technical Guidance will be used in conjunction with sound source characteristics, environmental factors that influence sound propagation, anticipated marine mammal occurrence and behavior near the activity, as well as other available activity-specific factors, to estimate the number and types of takes of marine mammals for a specific action. This document only addresses criteria for auditory impact (i.e., it does not address or make recommendations associated with sound propagation, marine mammal occurrence or density, or provide criteria for behavioral disturbance).

1.2 Addressing Uncertainty and Data Limitations

Inherent data limitations exist in many instances when assessing acoustic effects on marine mammal hearing. Data limitations, which make it difficult to account for uncertainty and variability, are not unique to assessing the effects of anthropogenic sound on marine mammals and are commonly encountered by resource managers (Ludwig et al. 1993; Francis and Shotton 1997; Harwood and Stokes 2003; Punt and Donovan 2007). Southall et al. (2019) and Finneran (2023) acknowledged the inherent data limitations when making recommendations for criteria to assess the effects of sound on marine mammals, including data available from a limited number of species, a limited number of individuals within a species, and/or a limited number of sound sources. Both Southall et al. (2019) and Finneran (2023) applied certain extrapolation procedures

[5] Mitigation and monitoring requirements associated with a Marine Mammal Protection Act (MMPA) authorization or an Endangered Species Act (ESA) consultation or permit are independent management decisions made in the context of the proposed activity and comprehensive effects analysis, and are beyond the scope of the Updated Technical Guidance. NMFS acknowledges exclusion zones and monitoring zones often correspond to criteria but that is not a legal requirement. However, the Updated Technical Guidance can be used to inform the development of mitigation or monitoring.

to estimate effects that had not been directly measured but that could be reasonably approximated using existing information and reasoned logic. The Updated Technical Guidance articulates where NMFS has faced such uncertainty and variability in the development of its criteria.

1.2.1 Assessment Framework

NMFS's approach applies a set of assumptions to address uncertainty in predicting potential auditory effects of sound on individual marine mammals. One of these assumptions includes the use of "representative" or surrogate individuals/species for establishing AUD INJ onset criteria for species where little to no data exists. The use of representative individuals/species is done as a matter of practicality (i.e., it is unlikely that adequate data will exist for all marine mammal species found worldwide or that we will be able to account for all sources of variability at an individual level) but is also scientifically based (i.e., taxonomy, hearing group). NMFS recognizes that additional applicable data may become available to better address many of these issues (e.g., uncertainty, surrogate species, etc.). As these new data become available, NMFS has an approach for updating this document (see Section III).

1.2.2 Data Standards

In assessing potential acoustic effects on marine mammals, as with any such issue facing the agency, standards for determining applicable data need to be articulated. Specifically, NOAA has Information Quality Guidelines[6] (IQG) for "ensuring and maximizing the quality, objectivity, utility, and integrity of information disseminated by the agency" (with each of these terms defined within the IQG). Further, the IQG stipulate that "To the degree that the agency action is based on science, NMFS will use (a) the best available science and supporting studies (including peer-reviewed science and supporting studies when available), conducted in accordance with sound and objective scientific practices, and (b) data collected by accepted methods or best available methods."

1.3 CHANGES ASSOCIATED WITH UPDATED TECHNICAL GUIDANCE

The overall methodology of deriving AUD INJ and TTS criteria presented in this Updated Technical Guidance is similar to the methodology described in the 2018 Revised Technical Guidance (NMFS 2018). However, there are some notable differences associated with new data and simplifications meant to align with methods and recommendations from Southall et al. (2019) (See Table 4 later in this document and Appendix A for more details).

Some of the main changes[7] include the following:

- Inclusion of updated marine mammal audiogram and TTS data made available since the publication of the 2018 Revised Technical Guidance

- Adoption of marine mammal hearing group terminology from Southall et al. 2019

[6] https://www.noaa.gov/organization/information-technology/policy-oversight/information-quality/information-quality-guidelines

[7] NMFS is aware that the National Marine Mammal Foundation successfully collected preliminary hearing data on two minke whales during their third field season (2023) in Norway. These data have implications for not only the generalized hearing range for low-frequency cetaceans but also on their weighting function. However, at this time, no official results have been published. Furthermore, a fourth field season (2024) is proposed, where more data will likely be collected. Thus, it is premature for us to propose any changes to our current Updated Technical Guidance. However, mysticete hearing data is identified as a special circumstance that could merit re-evaluating the acoustic criteria in this document. Therefore, we anticipate that once the data from both field seasons are published, it will likely necessitate updating this document (i.e., likely after the data gathered in the summer 2024 field season and associated analysis are published).

- Addition of in-air criteria for pinnipeds[8]

- Inclusion of the term "auditory injury (AUD INJ)" to replace "PTS"
  - Various studies with terrestrial mammals have reported recoverable noise-induced threshold shifts that result in neuropathy (e.g., Kujawa and Liberman 2009; Lin et al. 2011). Therefore, there are circumstances where auditory injury (AUD INJ) can occur, which may or may not result in PTS. Thus, the Updated Technical Guidance acknowledges that AUD INJ can occur, which includes but is not limited to PTS.

    The long-term consequences of this degeneration (i.e., synaptopathy or hidden hearing loss) remain unclear, since it cannot be measured directly in a living animal/human (Barbee et al. 2018; Le Prell et al. 2019). However, this degeneration is believed to contribute to the inability to detect sounds in noise, tinnitus, or hyperacusis (Barbee et al. 2018; Hickman et al. 2018). This topic is identified for future research not only for humans and terrestrial mammals but also in Appendix B of this document for marine mammals.

- Lower TTS and AUD INJ thresholds (SEL_{24h} metric) for HF[9] cetaceans, below 10 kHz, based on new data (Finneran et al. 2023a)

- Significantly lower TTS and AUD INJ thresholds (SEL_{24h} metric) for OW pinnipeds based on new data (Kastelein et al., 2021b; Kastelein et al., 2022a,b,c)

- New PW pinniped impulsive TTS onset data (Sills et al., 2020b), which affected the extrapolation (SEL_{24h} metric) for species without impulsive data

II. NMFS'S THRESHOLDS FOR ONSET OF PERMANENT THRESHOLD SHIFTS IN MARINE MAMMALS

The Updated Technical Guidance advances NMFS's assessment ability based upon the compilation, interpretation, and synthesis of the scientific literature. This document provides thresholds for the onset of AUD INJ based on characteristics defined at the acoustic source. Since only one study has reported measurements of PTS in a marine mammal (harbor seal; Reichmuth et al. 2019); AUD INJ onset thresholds have been extrapolated from marine mammal TTS measurements (i.e., using growth rates from terrestrial and marine mammal data). AUD INJ onset thresholds for all sound sources are divided into two broad categories: 1) impulsive and 2) non-impulsive. Thresholds are also presented as dual metric thresholds using weighted cumulative sound exposure level ($SEL_{24h,}$) and peak sound pressure level (PK SPL) metrics for impulsive sounds. As dual metrics, NMFS considers onset of AUD INJ to have occurred when either one of the two metrics is exceeded. For non-impulsive sounds, thresholds are provided using the weighted SEL_{24h} metric. Additionally, to account for the fact that different species groups use and hear sound differently (Table 1), marine mammals are sub-divided into seven broad hearing groups (i.e., LF, HF, and VHF cetaceans; PW, OW, PA, and OA pinnipeds; See Table 1 in next Section) and thresholds in the weighted SEL_{24h} metric incorporate auditory weighting functions.

[8] The Navy previously adopted in-air pinniped criteria in their previous document (DoN 2017). However, this is the first time NMFS has adopted in-air pinniped criteria in our Technical Guidance.

[9] In the Updated Technical Guidance, HF cetaceans refers to those species formerly referenced as MF cetaceans in the 2018 NMFS Revised Technical Guidance (NMFS 2018).

2.1 MARINE MAMMAL HEARING GROUPS

Current data (via direct behavioral and electrophysiological measurements) and predictions (based on inner ear morphology, modeling, behavior, vocalizations, or taxonomy) indicate that not all marine mammal species have equal hearing capabilities, in terms of absolute hearing sensitivity and the frequency band of hearing (Richardson et al. 1995; Wartzok and Ketten 1999; Southall et al. 2007; Au and Hastings 2008). Hearing has been directly measured in some odontocete and pinniped species (see reviews in Southall et al. 2007; Erbe et al. 2016; Southall et al. 2019). Direct measurements of mysticete hearing are lacking.[10] Thus, hearing predictions for mysticetes are based on other methods including: anatomical studies and modeling (Houser et al. 2001; Parks et al. 2007; Tubelli et al. 2012; Cranford and Krysl 2015[11]; Tubelli et al. 2018; Morris et al. 2023); vocalizations[12] (see reviews in Richardson et al. 1995; Wartzok and Ketten 1999; Au and Hastings 2008); taxonomy; and behavioral responses to sound (Dahlheim and Ljungblad 1990; see review in Reichmuth 2007; Frankel and Stein 2020). For the Updated Technical Guidance, NMFS has adopted the marine mammal hearing group designations from Southall et al. 2019.

Table 1 defines the updated generalized hearing ranges for each hearing group. This generalized hearing range was determined based on the ~65 dB[13] threshold from the composite audiograms. The generalized hearing ranges included in the Updated Technical Guidance are very similar to those in the previous version of the Technical Guidance (NMFS 2018) but with some modifications based on updated composite audiograms and individual species hearing ranges provided in Southall et al. 2019. Furthermore, there is the addition of in-air hearing ranges for PA and OA pinnipeds.

2.1.1 Application of Marine Mammal Hearing Groups

The application of marine mammal hearing groups occurs throughout the Updated Technical Guidance in two ways. First, thresholds are divided by hearing group to acknowledge that not all marine mammal species have identical hearing or susceptibility to noise-induced hearing loss[14] (NIHL). Outside the generalized hearing range, the risk of auditory impacts from sounds is considered highly unlikely or very low[15] (the exception would be if a sound above/below this

[10] There was an unsuccessful attempt to directly measure hearing in a stranded gray whale calf by Ridgway and Carder 2001. Furthermore, NMFS is aware that the National Marine Mammal Foundation successfully collected preliminary hearing data on two minke whales during their third field season (2023) in Norway. These data have implications for not only the generalized hearing range for low-frequency cetaceans but also on their weighting function. However, at this time, no official results have been published. Furthermore, a fourth field season (2024) is proposed, where more data will likely be collected. Thus, it is premature for us to propose any changes to our current Updated Technical Guidance. However, mysticete hearing data is identified as a special circumstance that could merit re-evaluating the acoustic criteria in this document. Therefore, we anticipate that once the data from both field seasons are published, it will likely necessitate updating this document (i.e., likely after the data gathered in the summer 2024 field season and associated analysis are published).

[11] Note: The modeling of Cranford and Krsyl (2015) predicts that the primary mechanism for hearing in LF cetaceans is bone conduction. Additionally, this predictive model was based on the skull geometry of a newborn fin whale.

[12] Studies in other species indicate that perception of frequencies may be broader than frequencies produced (e.g., Luther and Wiley 2009).

[13] In humans, hearing range is typically defined as 60 dB above the hearing threshold at greatest hearing sensitivity, and Southall et al. 2019 used 60 dB to indicate audiometry data by species. To account for uncertainty associated with marine mammal hearing, NMFS based the Updated Technical Guidance's generalized hearing range on 65 dB (which is broader than the hearing range definition for humans).

[14] NIHL is defined as a changes in normal auditory function that occur as a consequence of noise exposure, which can be temporary or permanent (Yost 2007; NIH 2022). NMFS intends this definition of NIHL to encompass both TTS and AUD INJ.

[15] Animals are able to detect sounds beyond their generalized hearing range (e.g., non-auditory mechanisms). However, typically, these sounds have to be extremely loud and would be considered uncomfortable (Wartzok and Ketten 1999). If a

range has the potential to cause physical injury, i.e., lung or gastrointestinal tract injury from underwater explosives).

Second, marine mammal hearing groups are used in the establishment of marine mammal auditory weighting functions discussed next.

Table 1: Marine mammal hearing groups.

Hearing Group^	Generalized Hearing Range*
UNDERWATER	
Low-frequency (LF) cetaceans (baleen whales)	7 Hz to 36[+] kHz
High-frequency (HF) cetaceans (dolphins, toothed whales, beaked whales, bottlenose whales)	150 Hz to 160 kHz
Very High-frequency (VHF) cetaceans (true porpoises, *Kogia*, river dolphins, cephalorhynchid, *Lagenorhynchus cruciger* & *L. australis*)	200 Hz to 165 kHz
Phocid pinnipeds (PW) (true seals)	40 Hz to 90 kHz
Otariid pinnipeds (OW) (sea lions and fur seals)	60 Hz to 68 kHz
IN-AIR	
Phocid pinnipeds (PA) (true seals)	42 Hz to 52 kHz
Otariid pinnipeds (OA) (sea lions and fur seals)	90 Hz to 40 kHz

^ Southall et al. 2019 indicates that as more data become available there may be separate hearing group designations for Very Low-Frequency cetaceans (blue, fin, right, and bowhead whales) and Mid-Frequency cetaceans (sperm, killer, and beaked whales). However, at this point, all baleen whales are part of the LF cetacean hearing group, and sperm, killer, and beaked whales are part of the HF cetacean hearing group. Additionally, recent data indicates that as more data become available for Monachinae seals, separate hearing group designations may be appropriate for the two phocid subfamilies (Ruscher et al. 2021; Sills et al. 2021).

* Represents the generalized hearing range for the entire group as a composite (i.e., all species within the group), where individual species' hearing ranges are may not be as broad. Generalized hearing range chosen based on ~65 dB threshold from composite audiogram, previous analysis in NMFS 2018, and/or data from Southall et al. 2007; Southall et al. 2019. Additionally, animals are able to detect very loud sounds above and below that "generalized" hearing range.

+ NMFS is aware that the National Marine Mammal Foundation successfully collected preliminary hearing data on two minke whales during their third field season (2023) in Norway. These data have implications for not only the generalized hearing range for low-frequency cetaceans but also on their weighting function. However, at this time, no official results have been published. Furthermore, a fourth field season (2024) is proposed, where more data will likely be collected. Thus, it is premature for us to propose any changes to our current Updated Technical Guidance. However, mysticete hearing data is identified as a special circumstance that could merit re-evaluating the acoustic criteria in this document. Therefore, we anticipate that once the data from both field seasons are published, it will likely necessitate updating this document (i.e., likely after the data gathered in the summer 2024 field season and associated analysis are published).

sound is on the edge of a hearing group's generalized hearing range and there is the potential for exposure to high sound pressure levels, then consider the potential for detection beyond normal auditory pathways. Thus, generalized hearing ranges do not provide an absolute cutoff, beyond which noise impacts are irrelevant or even unlikely. This depends on many factors, including the target species and characteristics of the noise (spectrum, amplitude, etc.) in question.

2.2 MARINE MAMMAL AUDITORY WEIGHTING FUNCTIONS

The ability to hear sounds varies across a species' hearing range. Most mammal audiograms have a typical "U-shape," with frequencies at the bottom of the "U" being those to which the animal is more sensitive, in terms of hearing (i.e. the animal's best hearing range; for an example audiogram, see Glossary, Figure F1). Auditory weighting functions best reflect an animal's ability to hear a sound (and do not necessarily reflect how an animal will perceive and behaviorally react to that sound). To reflect higher hearing sensitivity at particular frequencies, sounds are often weighted. For example, A-weighting (developed for human hearing) deemphasizes frequencies below 1 kHz and above 6 kHz based on the inverse of the idealized (smoothed) 40-phon equal loudness hearing function across frequencies, standardized to 0 dB at 1 kHz (e.g., Harris 1998). Other types of weighting functions (e.g., B, C, D) deemphasize different frequencies to different extremes (e.g., flattens equal-loudness perception across wider frequencies with increasing received level; for example, C-weighting is uniform from 50 Hz to 5 kHz; ANSI 2011).

Auditory weighting functions have been proposed for marine mammals, specifically associated with AUD INJ onset thresholds expressed in the weighted SEL_{24h} [16] metric, which take into account what is known about marine mammal hearing (Southall et al. 2007; Erbe et al. 2016; Southall et al. 2019).

Upon evaluation, NMFS determined that the proposed methodology in Finneran 2024 reflects the scientific literature and therefore NMFS incorporated it directly into this Updated Technical Guidance (Appendix A) following an independent peer review (see Appendix C for details on peer review and link to Peer Review Report).

2.2.1 Use of Auditory Weighting Functions in Assessing Susceptibility to Noise-Induced Hearing Loss

Auditory weighting functions are used for human noise standards to assess the overall hazard of noise on hearing. Specifically, human auditory weighting functions provide a "rating that indicates the injurious effects of noise on human hearing" (OSHA 2013). Thus, while these functions are based on regions of equal loudness and best hearing, in the context of human risk assessments, as well as their use in the Updated Technical Guidance, they are meant to reflect the susceptibility of the ear to noise-induced threshold shifts (TS). Regions of enhanced susceptibility to noise may not perfectly mirror a species' region of best hearing (e.g., TTS measurements from harbor seals; bottlenose dolphin, belugas, harbor porpoise, and Yangtze finless porpoise support this; Popov et al. 2011a; Finneran and Schlundt 2013; Popov et al. 2015; Gransier and Kastelein 2024). Thus, within the Updated Technical Guidance, auditory weighting functions are meant to assess risk of NIHL and do not necessarily encompass the entire range of best hearing for every species within the hearing group.

2.2.2 Marine Mammal Auditory Weighting Functions

Frequency-dependent marine mammal auditory weighting functions were derived using data on hearing ability (composite audiograms), effects of noise on hearing, and data on equal latency (Finneran 2024). Separate functions were derived for each marine mammal hearing group (Figures 1-3).

[16] Auditory weighting functions are not to be applied to AUD INJ or TTS onset criteria expressed as the PK SPL metric (i.e., PK SPL criteria are flat or unweighted within the generalized hearing range of marine mammals, 7 Hz to 165 kHz). Furthermore, the weighting functions in this document are only appropriate to examine noise-induced hearing loss (i.e., they are not appropriate for examining behavioral disturbance).

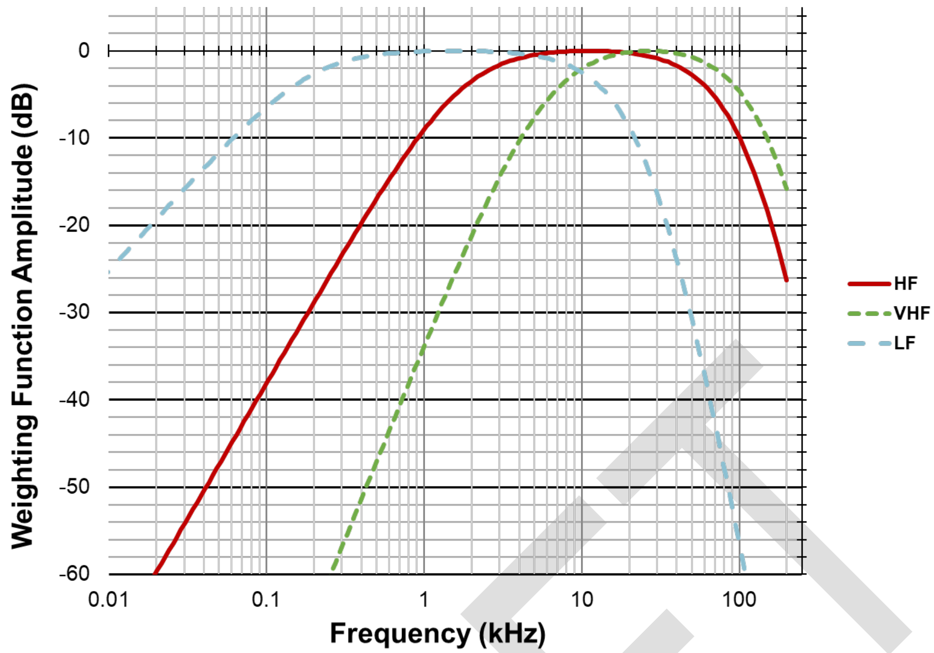

Figure 1: **Auditory weighting functions for low-frequency (LF; blue dashed line), high-frequency (HF; red solid line), and very high-frequency (VHF; green dotted line) cetaceans.**

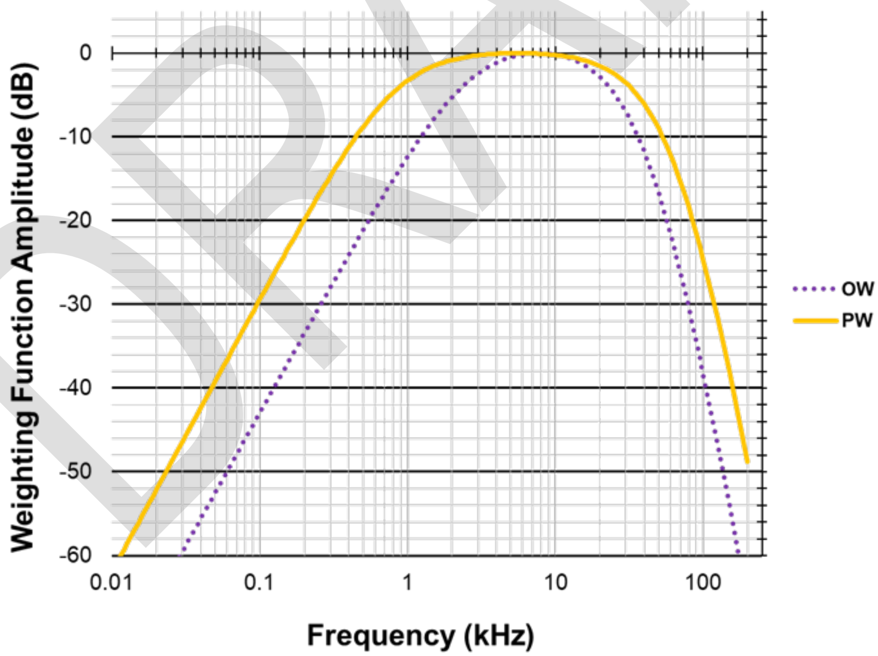

Figure 2: **Underwater auditory weighting functions for otariid (OW; purple dotted line) and phocid (PW; orange solid line) pinnipeds.**

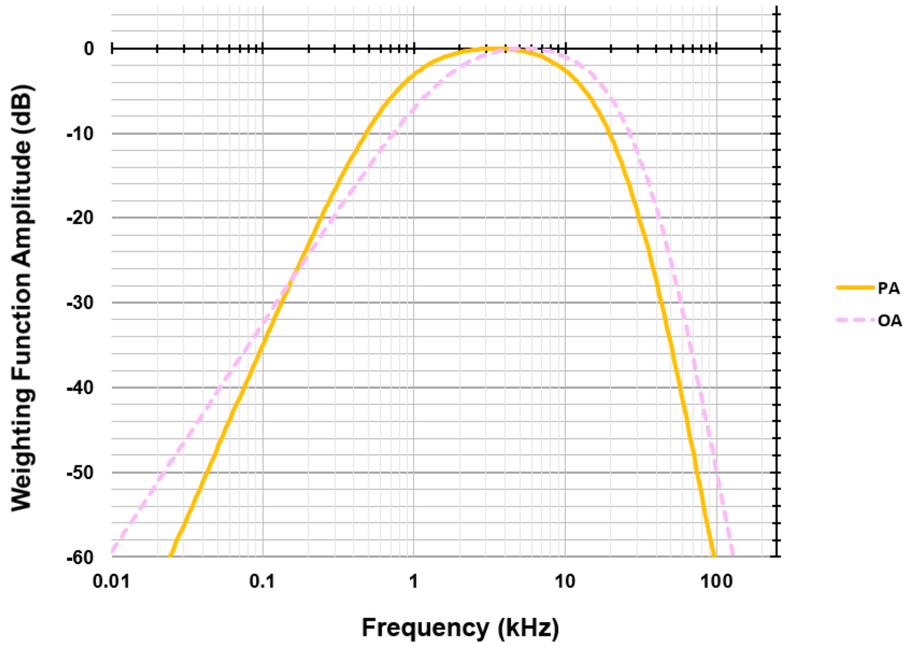

Figure 3: In-air auditory weighting functions for otariid (OA; dashed pink line) and phocid (PA; solid yellow line) pinnipeds.

The overall shape of the auditory weighting functions is based on a generic band-pass filter described by Equation 1:

$$W(f) = C + 10\log_{10}\left\{\frac{(f/f_1)^{2a}}{[1+(f/f_1)^2]^a\,[1+(f/f_2)^2]^b}\right\} \quad \text{dB} \qquad \textbf{Equation 1}$$

where $W(f)$ is the auditory weighting function amplitude in decibels (dB) at a particular frequency (f) in kilohertz (kHz)[17]. The function shape is determined by the following auditory weighting function parameters:

- Low-frequency exponent (a) (dimensionless): This parameter determines the rate at which the weighting function amplitude declines with frequency at the lower frequencies. As the frequency decreases, the change in amplitude becomes linear with the logarithm of frequency with a slope of $20a$ dB/decade. Larger values of a result in lower weighting function amplitudes at f_1 and steeper roll-offs at frequencies below f_1.

- High-frequency exponent (b) (dimensionless): This is the rate at which the weighting function amplitude declines with frequency at the upper frequencies. As the frequency increases, the change in amplitude becomes linear with the logarithm of frequency with a slope of $20b$ dB/decade. Larger values of b result in lower weighting function amplitudes at f_2 and steeper roll-offs at frequencies above f_2.

- Low-frequency cutoff (f_1) (kHz): This parameter defines the lower limit of the band-pass filter (i.e., the lower frequency where weighting function amplitude begins to roll off or

[17] Where 0 dB indicates maximum susceptibility to NIHL.

decline from the flat, central portion of the function). This parameter is directly dependent on the value of the low-frequency exponent (a). Decreasing f_1 will enlarge the pass-band of the function (the flat, central portion of the curve).

- High-frequency cutoff (f_2) (kHz): This parameter defines the upper limit of the band-pass filter (i.e., the upper frequency where weighting function amplitude begins to roll off or decline from the flat, central portion of the function). This parameter is directly dependent on the value of the high-frequency exponent (b). Increasing f_2 will enlarge the pass-band of the function.

- Weighting function gain (C) (dB): This parameter determines the vertical position of the function and is adjusted to set the maximum amplitude of the auditory weighting function to 0 dB. Changing the value of C shifts the function up/down.

Finneran (2023) illustrates the influence of each parameter value on the shape of the auditory weighting function (Appendix A).

In association with auditory weighting functions are exposure functions that illustrate how auditory weighting functions relate to auditory thresholds. Auditory exposure functions (Equation 2) are the inversion of Equation 1:

$$E(f) = K - 10\log_{10}\left\{\frac{(f/f_1)^{2a}}{[1+(f/f_1)^2]^a\,[1+(f/f_2)^2]^b}\right\} \quad \text{dB} \qquad \textbf{Equation 2}$$

where $E(f)$ is the acoustic exposure as a function of frequency (f) and the gain parameter constant (K), which is adjusted to set the minimum value of the curve to the weighted AUD INJ/TTS onset auditory threshold. All other parameters are the same as those in Equation 1. Figure 4 illustrates how the various weighting parameters relate to one another in both the auditory weighting and exposure functions.

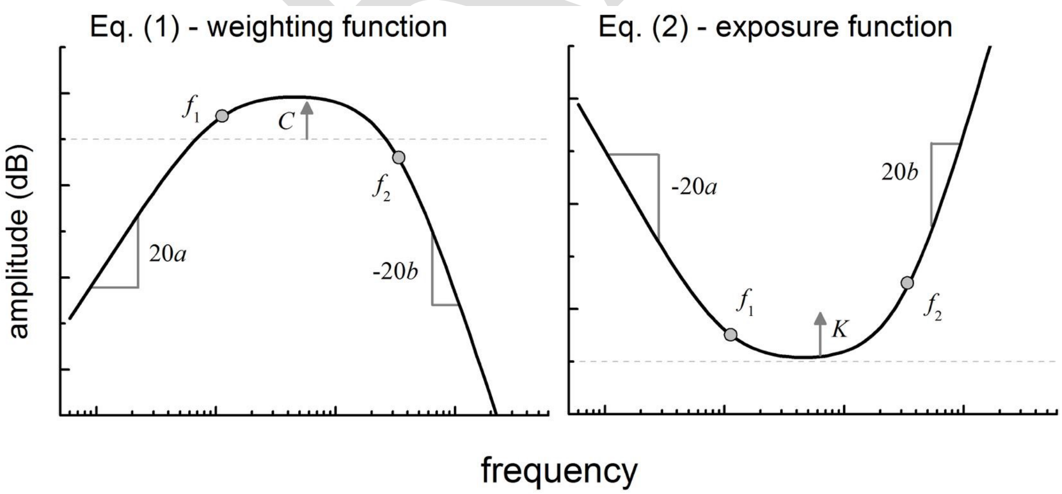

Figure 4: Illustration of function parameter in both auditory weighting functions and exposure functions (from Finneran 2024). Reference to Equations 1 and 2 match those in the Updated Technical Guidance.

2.2.3 Derivation of Function Parameters

Numeric values associated with auditory weighting function parameters were derived from available data from audiograms (measured and predicted), equal latency contours, and marine mammal TTS data using the following steps from Finneran (2023):

1. Marine mammals are divided into their appropriate hearing groups (See Table 1).

2. Marine mammal composite audiograms were derived for each hearing group.

   In deriving marine mammal composite audiograms, an informal data hierarchy was established in terms of assessing these types of data. Specifically, audiograms obtained via behavioral methodologies were determined to provide the most representative (sensitive) presentation of hearing ability (Finneran et al. 2007a; Finneran 2024), followed by auditory evoked potential (AEP) data,[18] and lastly by mathematical/anatomical models for species where no data are available (i.e., LF cetaceans). Thus, the highest quality data available for a specific hearing group were used (Table 2).[19]

   For LF cetaceans, only two studies were available for consideration (i.e., predicted audiograms for a humpback whale from Houser et al. 2001 and a fin whale from Cranford and Krysl 2015), which alone was not enough to derive a predicted audiogram for this entire hearing group. Thus, an alternative approach was used to derive a composite audiogram and associated auditory weighting function for LF cetaceans (i.e., composite audiogram parameters had to be predicted; for specifics on this process, see Appendix A.1).

   An animal's individual data were included only once at a particular frequency. If data from the same individual were available from multiple studies, typically the earlier published data were used (e.g., individual was younger and less likely to exhibit age-related hearing loss). Furthermore, data from individuals with obvious high-frequency hearing loss for their species or aberrant audiograms were excluded.

   To combine individual datasets, a common set of frequency values was required. Thus, frequency values for each individual were replaced with frequencies spaced at 1/12-octave intervals, encompassing the range of frequencies present in the original data. Threshold values at the 1/12-octave frequencies were obtained by linear-log interpolation (linear thresholds, logarithmic frequencies) between sequential data points, as shown in Figure 5.

[18] Despite not directly including AEP audiograms in the development of a hearing groups' composite audiogram, these data were evaluated to ensure species were placed within the appropriate hearing group and to ensure a species where only AEP data are available were within the bounds of the composite audiogram for that hearing group. Furthermore, AEP TTS data are presented within the Updated Technical Guidance for comparative purposes alongside TTS data collected by behavioral methods illustrating that the AEP TTS data are within the bounds (the majority of the time above) of those collected by behavioral methods.

[19] Behavioral techniques for obtaining audiograms measure perception of sound by a receiver, while AEP methods measure only neural activity (Jewett and Williston 1971) (i.e., the two methodologies are not necessarily equivalent). As a result, behavioral techniques consistently produce lower thresholds than those obtained by AEPs (e.g., Szymanski et al. 1999; Yuen et al. 2005; Houser and Finneran 2006). Currently, there are no means established for "correcting" AEP data so that it may be more comparable to those obtained via behavioral methods (Heffner and Heffner 2003; Finneran 2015; Sisneros et al. 2016; Erbe et al. 2016).

Table 2: Summary of data available for deriving composite audiograms.†

Hearing Group	Species (number of individuals)	References (new references added for Updated Technical Guidance are in italics)
UNDERWATER		
High-Frequency (HF) Cetaceans	Beluga (9)	White et al. 1978; Awbrey et al. 1988; Johnson et al. 1989; Ridgway et al. 2001; Finneran et al. 2005b
	Bottlenose dolphin (3)	Johnson 1967; Lemonds et al. 2011; Finneran et al. 2010a
	False killer whale (1)	Thomas et al. 1988
	Killer whale (8)	Szymanski et al. 1999; *Branstetter et al. 2017*
	Pacific white-sided dolphin (1)	Tremel et al. 1996
	Striped dolphin (1)	Kastelein et al. 2003
	Tucuxi (1)	Sauerland and Dehnhardt 1998
Very High-Frequency (VHF) Cetaceans	Amazon River dolphin (1)	Jacobs and Hall 1972
	Harbor porpoise (5)	Kastelein et al. 2002b; Kastelein et al. 2010; Kastelein et al. 2015c; *Kastelein et al. 2017a*
Phocid Pinnipeds (PW)	Harbor seal (5)	Terhune 1988; Kastelein et al. 2009b; Reichmuth et al. 2013; *Cunningham and Reichmuth 2016*
	Bearded sealed (2)	*Sills et al. 2020a*
	Hawaiian monk seal (1)	*Sills et al. 2021*
	Harp seal (1)	*Terhune et al. 1972*
	Northern elephant seal (1)	Kastak and Schusterman 1999
	Ringed seal (1)	Sills et al. 2015
	Spotted seal (3)	Sills et al. 2014; *Cunningham and Reichmuth 2016*
Otariid Pinnipeds* (OW)	California sea lion (6)	*Kastak and Schusterman 1998*; Mulsow et al. 2012; Reichmuth and Southall 2012; Reichmuth et al. 2013; *Cunningham and Reichmuth 2016; Kastelein et al. 2023a*
	Northern fur seal (3)	Moore and Schusterman 1987; Babushina et al. 1991
	Steller sea lion (2)	Kastelein et al. 2005a
IN-AIR		
Phocid Pinnipeds (PA)	Harbor seal (1)	*Reichmuth et al. 2013*
	Spotted seal (2)	*Sills et al. 2014*
	Ringed seal (1)	*Sills et al. 2015*
Otariid Pinnipeds* (OA)	California sea lion (4)	*Moore and Schusterman 1987; Mulsow et al. 2011a; Reichmuth et al. 2013; Reichmuth et al. 2017*
	Steller sea lion (1)	*Mulsow et al. 2010*
	Northern fur seal (3)	*Moore and Schusterman 1987; Babushina et al. 1991*

† More details on individual subjects are available in Appendix A.1. Some datasets were excluded due to subjects having high-frequency hearing loss or aberrant audiograms. The most common reasons for excluding an individual's data were abnormal audiograms featuring high-frequency hearing loss (typically seen in older animals) or "notches" in the audiogram, or data collected in the presence of relatively high ambient noise that resulted in elevated thresholds. Excluding these data ensured that the composite audiograms were not artificially elevated, which could result in unrealistically high thresholds. See Appendix A.1 for details on excluded datasets.

NMFS is aware that the National Marine Mammal Foundation successfully collected preliminary hearing data on two minke whales during their third field season (2023) in Norway. These data have implications for not only the generalized hearing range for low-frequency cetaceans but also on their weighting function. However, at this time, no official results have been published. Furthermore, a fourth field season (2024) is proposed, where more data will likely be collected. Thus, it is premature for us to propose any changes to our current Updated Technical Guidance. However, mysticete hearing data is identified as a special circumstance that could merit re-evaluating the acoustic criteria in this document. Therefore, we anticipate that once the data from both field seasons are published, it will likely necessitate updating this document (i.e., likely after the data gathered in the summer 2024 field season and associated analysis are published).

* The otariid pinniped (underwater) hearing group's composite audiogram also contains data from a single Pacific walrus (*Odobenus rosmarus*) from Kastelein et al. 2002a and a single sea otter (*Enhydra lutris nereis*) from Ghoul and Reichmuth 2014. The otariid pinniped (in air) hearing group's composite audiogram contains data from a single sea otter (*Enhydra lutris nereis*) from Ghoul and Reichmuth 2014 and five polar bears from Owen and Bowles 2011. These species are under the jurisdiction of the USFWS. However, since marine mammal audiogram data are limited, a decision was made to include all available datasets from in-water and in-air groups to derive composite audiograms for these hearing groups.

From these data, the median threshold value was calculated at each frequency and fit by the function:

$$T(f) = T_0 + A \log_{10}\left(1 + \frac{F_1}{f}\right) + \left(\frac{f}{F_2}\right)^B \qquad \textbf{Equation 3}$$

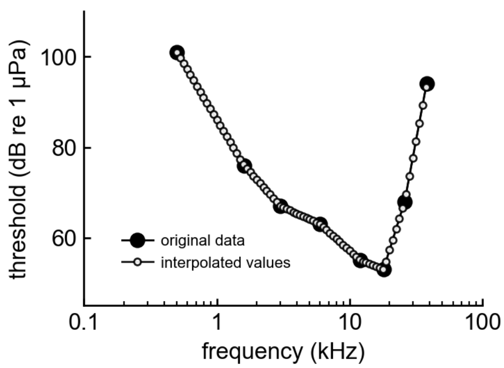

Figure 5. Illustration of interpolation used to ensure common frequencies across studies. Threshold data for each study were interpolated onto a grid of frequencies, logarithmically spaced at 1/12-octave intervals (Finneran 2024).

where $T(f)$ is the threshold at frequency f, and T_0, F_1, F_2, A, and B are fitting parameters. The median value was used to reduce the influence of outliers. The particular form of Equation 3 was chosen to provide linear-log roll-off with variable slope at low frequencies and a steep rise at high frequencies. Equation 3 was fit to the median threshold data using the *curve_fit* function in the optimize module of the python package SciPy (Virtanen et al., 2020).

The composite audiogram fitting parameters are presented in Table 3, with the resulting composite audiograms presented in Figure 6.

Table 3: Composite audiogram fitting parameters by hearing group.

Group	T_0 (dB)	F_1 (kHz)	F_2 (kHz)	*A*	*B*	Minimum threshold (RMS SPL dB)
UNDERWATER						
LF cetacean	54.2	0.412	3.73	20.0	1.79	56
HF cetacean	-38.9	9910	10.5	33.5	1.66	51
VHF cetacean	48.2	4.95	132	46.8	24.5	49
Phocid pinniped	55.1	0.391	8.56	48.4	1.79	57
Otariid pinniped	9.90	74.0	0.17	33.3	0.786	64
IN-AIR						
Phocid pinniped	-36.2	2.38	0.0188	52.6	0.581	-3.8
Otariid pinniped	6.9	1.04	8.86	63.7	2.78	11

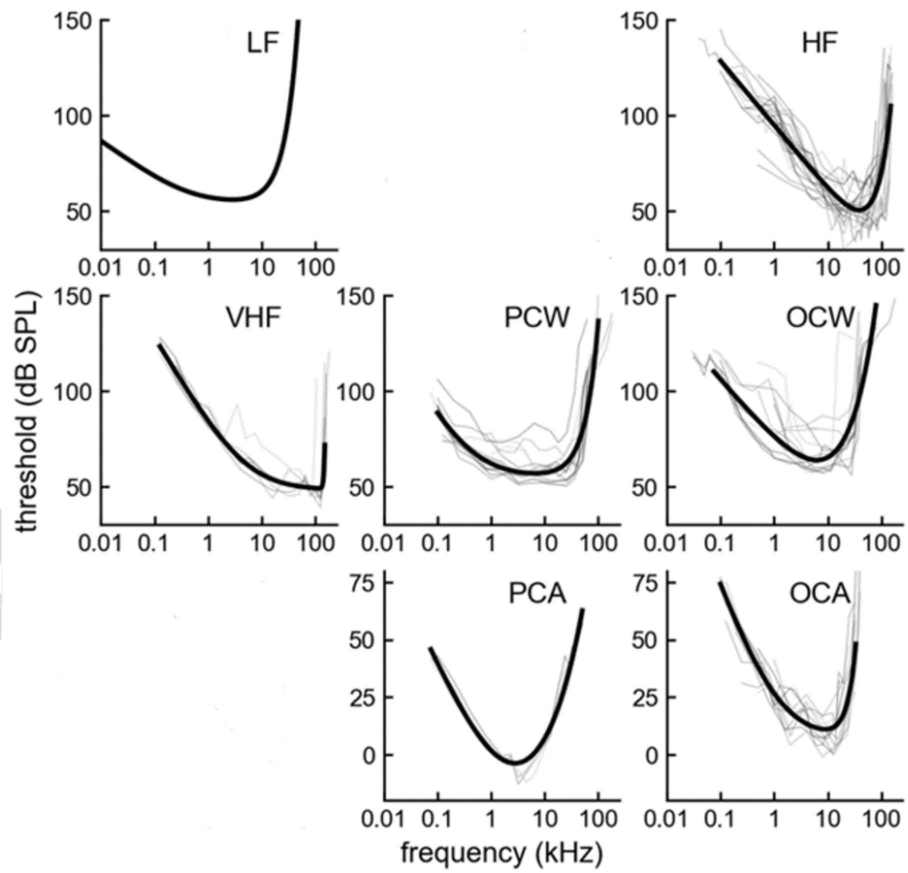

Figure 6: Resulting composite audiograms for low-frequency (LF), high-frequency (HF), and very high-frequency cetaceans (VHF), phocid (PW) and otariid (OW) pinnipeds underwater, and phocid (PA) and otariid (OA) pinnipeds in air (from Finneran 2024). Thin lines represent the threshold data from individual animals, while thick lines represent the composite audiograms. Thresholds are expressed in RMS SPL dB re: 1 µPa for underwater data and RMS SPL dB re: 20 µPa for in-air data (Finneran 2024).

3. Derivation of the weighting functions low-frequency exponent (a).

   This exponent was defined using the smaller of the low-frequency slope from either the composite audiogram or the lower-frequency slope of the equal latency contours (if available) and then divided by twenty (s0/20). This results in the slope matching the shallower slope of the audiogram.

4. Derivation of the weighting functions high-frequency exponent (b).

   This exponent was set equal to five, which is higher than what was used in the previous Technical Guidance (NMFS 2018) (b=2). The value was increased to fit better the OW pinniped function without substantially affecting the other group fits.

5. Derivation of low- (f_1) and high-frequency cutoffs (f_2).

   For groups with TTS onset data (HF cetaceans, VHF cetaceans, OW pinnipeds, and PW pinnipeds), nonlinear regression was used to find values of K, f_1, and f_2 to best-fit Equation 2. Nonlinear regression was performed using the *curve_fit* function in the optimize module of the python package SciPy (Virtanen et al., 2020).

   For some datasets, Equation 2 can exhibit high dependency among the parameters, resulting in small changes in the function despite large changes in parameter values. This can cause problems in extrapolating to the other groups. Therefore, the optimization process was constrained so that $f_L \leq f_1 \leq F_0$ and $F_0 \leq f_2 \leq f_H$, where f_L and f_H are the frequencies below and above F_0 (the composite audiogram frequency of best hearing), respectively, where the composite audiogram thresholds were 40 dB above the minimum audiogram threshold at F_0.

   Following each curve-fit, the frequencies at which the resulting exposure function amplitude exceeded the minimum value by 10 dB were compared to the corresponding frequencies for the composite audiogram (Figure 7). If the lower exposure function frequency was above the audiogram frequency, the parameter f_1 was adjusted downward until the exposure function and audiogram frequencies matched. Similarly, if the upper exposure function frequency was below the audiogram frequency, the parameter f_2 was adjusted upward until the exposure function and audiogram frequencies matched. This procedure ensured that the exposure function 10-dB bandwidth was at least as wide as the audiogram, since it is expected that the high sound levels capable of causing TTS would cause the exposure function to “flatten” relative to the audiogram. The practical effect of this step was to decrease f_1 for the PW and OW pinnipeds and increase f_2 for the VHF group.

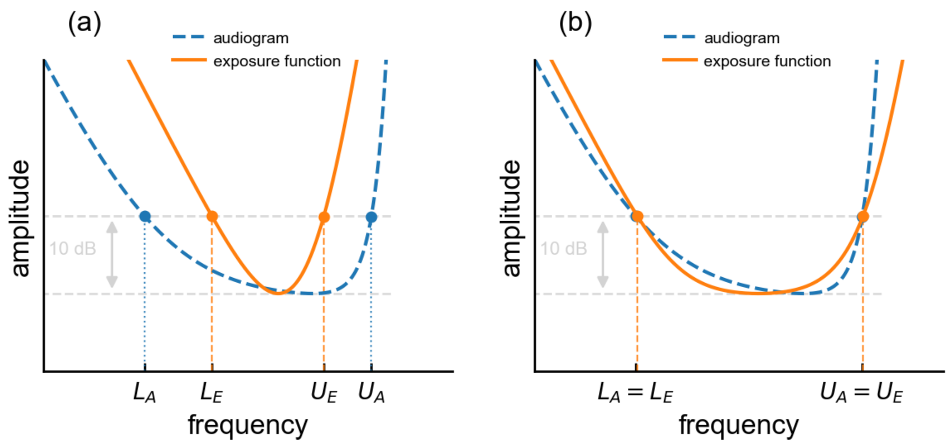

Figure 7: **(a) After fitting Equation 2 to the onset TTS data, the frequencies at which the exposure function amplitude was 10 dB above the minimum (L_E and U_E) were compared to the corresponding frequencies in the composite audiogram (L_A and U_A, respectively). (b) If $L_E > L_A$, then f_1 in Equation 2 was iteratively decreased until $L_E = L_A$. Similarly, if $U_E < U_A$, f_2 in Equation 2 was iteratively increased until $U_E = U_A$ (Finneran 2024).**

To determine f_1 and f_2 for the remaining groups (without TTS data), the parameters ΔT_1 and ΔT_2 were defined, such that ΔT_1 was the amount that the composite audiogram threshold at f_1 exceeded the minimum threshold value, and ΔT_2 was the amount that the composite audiogram threshold at f_2 exceeded the minimum threshold value (Figure 8).

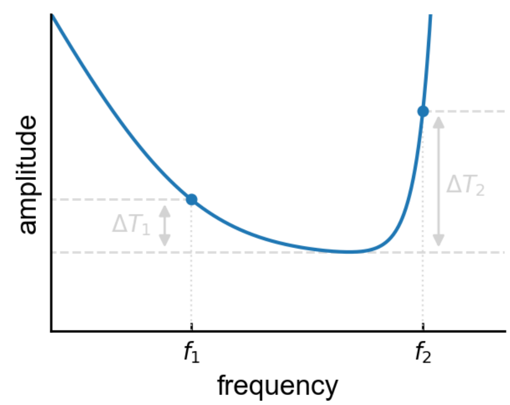

Figure 8: **The parameter ΔT_1 was defined as the amount that the composite audiogram threshold at f_1 exceeded the minimum threshold value. Similarly, ΔT_2 was defined as the amount that the composite audiogram threshold at f_2 exceeded the minimum threshold value (Finneran 2024).**

After determining the best-fit values of f_1, f_2, and K for groups HF cetaceans, VHF cetaceans, OW pinnipeds, and PW pinnipeds, ΔT_1 and ΔT_2 were determined for each group (i.e., ΔT_1 = 36.8, 11.5, 3.9, 6.5 dB and ΔT_2 = 38.6, 22.7, 38.9, 39.4 dB, for HF cetaceans, VHF cetaceans, OW pinnipeds, and PW pinnipeds, respectively). For ΔT_1, the value at 36.8 appears to be an outlier. Thus, the median value of ΔT_1 (9.0 dB) and the mean of ΔT_2 (34.9 dB) were used in conjunction with the composite audiograms for the LF cetaceans, PA pinnipeds, and OA pinniped to determine f_1 and f_2.

6. Incorporation of TTS data.

   As with previous Technical Guidance, only TTS data from psychophysical (behavioral) hearing tests were used. TTS data are available from HF and VHF cetaceans, PW and OW pinnipeds, and PA and OA pinnipeds to determine TTS onset. For LF cetaceans, where data were not available, TTS onset was estimated by assuming the numeric difference between auditory threshold and TTS onset at the frequency of best hearing ($f0$) would be similar across hearing groups. For LF cetaceans auditory threshold had to be predicted, since no data exist (For specifics on methodology, see Appendix A.2).

   More information on the incorporation of TTS data is included in Section 2.3.3 later in this document.

7. Derivation of the weighting function parameter (C).

   This exponent was determined by substituting parameters a, b, f_1, and f_2 in Equation 1 and setting the peak amplitude of the function to zero.

Table 4 summarizes the basic steps in process, with a comparison of what changed between our 2018 Revised Technical Guidance (NMFS 2018) and this Updated Technical Guidance document.

For each hearing group, the resulting numeric values associated with these parameters and resulting weighted TTS onset threshold for non-impulsive sources (weighted SEL_{24h} metric) are listed in Table 5 and resulting auditory weighting functions are depicted in Figures 1 through 3.

Table 4: Steps used to define weighting function and exposure function parameters in Equations 1 and 2 for between the previous version of the Technical Guidance (NMFS 2018) and Updated Technical Guidance (NMFS 2024)

Step	NMFS 2018	NMFS 2024 (changes from NMFS 2018 are in italics)
1	Marine mammals divided into hearing groups	Same as previous 2018 Revised Technical Guidance*, with addition of in-air pinniped groups and naming convention following Southall et al. 2019.*
2	Composite audiogram derived for each hearing group	Same as previous 2018 Revised Technical Guidance, *with addition of in-air pinniped groups and naming convention following Southall et al. 2019.*
3	The exponent *a* was defined as the smaller of the low frequency slope from the audiogram and equal latency contour.	Same as previous 2018 Revised Technical Guidance
4	The exponent *b* was set equal to two.	*The exponent b was set equal to five.*

Step	NMFS 2018	NMFS 2024 (changes from NMFS 2018 are in italics)
5	*f_1 and f_2 were defined as the frequencies where composite audiogram thresholds were ΔT-dB above the lowest threshold.* *For groups with sufficient onset TTS data, the optimum value of ΔT was found by adjusting ΔT to best-fit Equation 2 to the non-impulsive TTS onset data. This value of ΔT was used for the remaining groups.* *The parameter K was then adjusted to fit Equating 2 to available or estimated TTS onset data.*	*For the groups with sufficient onset TTS data (HF cetaceans, VHF cetaceans, PW pinnipeds and OW pinnipeds), the parameters f_1, f_2, and K were adjusted to fit Equation 2 to the non-impulsive TTS onset data. If the resulting exposure function bandwidth, defined as 10 dB above the minimum TTS onset value, did not meet or exceed that of the composite audiogram, f_1 was decreased and/or f_2 increased as necessary to ensure that the 10-dB bandwidth criterion was met.* *For the remaining groups, f_1 and f_2 were defined so the differences between the audiogram thresholds at f_1 and f_2 and the minimum threshold (ΔT_1 and ΔT_2, respectively) matched the median value of ΔT_1 and mean value of ΔT_2 for the HF cetaceans, VHF cetaceans, PW pinnipeds, and OW pinnipeds). The parameter K was then adjusted to fit Equation 2 to available or estimated TTS onset data.*
6	The non-impulsive, weighted TTS threshold was defined as the minimum of the TTS exposure function.	Same as previous 2018 Revised Technical Guidance
7	The parameter *C* was defined to set the peak amplitude of the weighting function to zero.	Same as previous 2018 Revised Technical Guidance

Table 5: Summary of auditory weighting and exposure function parameters.

Hearing Group	a	b	f_1 (kHz)	f_2 (kHz)	C (dB)	K (dB)	Weighted TTS onset threshold* (SEL_{24h})
UNDERWATER							
Low-frequency (LF) cetaceans	0.99	5	0.168	26.6	0.12	177	177 dB
High-frequency (HF) cetaceans	1.55	5	1.73	129	0.32	181	181 dB
Very High-frequency (VHF) cetaceans	2.23	5	5.93	186	0.91	160	161 dB
Phocid pinnipeds (PW)	1.63	5	0.81	68.3	0.29	175	175 dB
Otariid pinnipeds (OW)	1.58	5	2.53	48.3	1.37	178	179 dB
IN-AIR							
Phocid pinnipeds (PA)	2.05	5	0.74	24.4	0.83	133	134 dB
Otariid pinnipeds (OA)	1.35	5	1.75	32.5	1.18	156	157 dB

* Determined from minimum value of auditory exposure function and the weighting function at its peak (i.e., mathematically equivalent to $K + C$).

2.2.4 Application of Marine Mammal Auditory Weighting Functions for AUD INJ Onset Thresholds

The application of marine mammal auditory weighting functions emphasizes the importance of making measurements and characterizing sound sources in terms of their overlap with biologically-important frequencies (e.g., frequencies used for environmental awareness, communication or the detection of predators or prey), and not only the frequencies of interest or concern for the completion of the sound-producing activity (i.e., context of sound source).

If the frequencies produced by a sound source are outside a hearing group's most susceptible hearing range (where the auditory weighting function amplitude is < 0 dB), sounds at those frequencies need to have a higher sound pressure level to produce a similar threshold shift (i.e., AUD INJ onset) as sounds with frequencies in the hearing group's most susceptible hearing range. Because auditory weighting functions take into account a hearing group's differing susceptibility to frequencies, the implementation of these functions typically results in smaller isopleths[20] for frequencies where the group is less susceptible. Additionally, if the sound source produces frequencies completely outside the generalized hearing range of a given hearing group (i.e., has no harmonics/subharmonics that are capable of producing sound within the hearing range of a hearing group), then the likelihood of the sound causing hearing loss is considered low.[21]

Marine mammal auditory weighting functions are used in conjunction with corresponding weighted SEL_{24h} AUD INJ onset criteria. If the use of the full auditory weighting function is not possible by an action proponent (i.e., consider auditory weighting function over multiple frequencies for broadband source), NMFS has provided an alternative tool based on a simpler auditory weighting function (See NMFS Optional User Spreadsheet Tool).

Tougaard et al. (2015) reviewed the impacts of using auditory weighting functions and various considerations when applying them during the data evaluation and implementation stages (e.g., consequences of using too broad or too narrow of a filter) and suggested some modifications (correction factors) to account for these considerations. However, there are no data to support doing so (i.e., selection would be arbitrary). Moreover, various conservative factors have been accounted for in the development of auditory weighting functions and thresholds: a 6 dB threshold shift was used to represent TTS onset; the methodology does not incorporate exposures where TTS did not occur; and the potential for recovery is not accounted for. Additionally, the means by which NMFS is applying auditory weighting functions is supported and consistent with what has been done for humans (i.e., A-weighted thresholds used in conjunction with A-weighting during implementation).

2.2.4.1 Measuring and Maintaining Full Spectrum for Future Analysis

It is recommended that marine mammal auditory weighting functions be applied after sound field measurements[22] have been obtained (i.e., post-processing), with the total spectrum of sound

[20] Note: Criteria associated with a hearing group do not change depending on how much a sound may overlap a group's most susceptible frequency range. Instead, weighting functions affect exposure modeling/analysis via the resulting size of the isopleth (area) associated with the criteria based on how susceptible that particular hearing group is to the sound being modeled. For example, a hearing group could have different size isopleths associated with the same criteria, if one sound was within its most susceptible frequency range and the other was not (i.e., sound in most susceptible hearing range will result in larger isopleth compared to sound outside the most susceptible hearing range).

[21] The potential for sound to damage beyond the level the ear can perceive exists (Akay 1978), which is why the criteria also include the PK SPL metric, which is flat or unweighted within the generalized hearing range of a hearing group.

[22] Note: Sound field measurements refers to actual field measurements, which are not a requirement of this Updated Technical Guidance, and not to exposure modeling analyses, where it may be impractical due to data storage and cataloging restraints.

preserved for later analysis (i.e., if auditory weighting functions are updated or if there is interest in additional species, then data can still be used). Additionally, it is important to consider measurements that encompass the entire frequency band that a sound source may be capable of producing (i.e., sources often produce sounds, like harmonics/subharmonics, beyond the frequency/band of interest; e.g., Deng et al. 2014; Hastie et al. 2014).

2.3 AUD INJ Onset Criteria

Available data from humans and other terrestrial mammals indicate that a 40 dB threshold shift approximates AUD INJ onset (see Ward et al. 1958; Ward et al. 1959; Ward 1960; Kryter et al. 1966; Miller 1974; Ahroon et al. 1996; Henderson et al. 2008). Southall et al. (2007) also recommended this definition of PTS onset.

Studies to induce and measure AUD INJ onset criteria for marine mammals are not pursued.[23] Instead, these criteria are extrapolated from available TTS onset measurements. Thus, based on cetacean measurements from TTS studies (see Southall et al. 2007; Finneran 2015; Southall et al. 2019; and Finneran 2024 found in Appendix A of this Updated Technical Guidance) a threshold shift of 6 dB is considered the minimum threshold shift clearly larger than any day-to-day or session-to-session variation[24] in a subject's normal hearing ability and is typically the minimum amount of threshold shift that can be differentiated in most experimental conditions (Finneran et al. 2000; Schlundt et al. 2000; Finneran et al. 2002). Thus, NMFS has set the onset of TTS at the lowest level that exceeds recorded variation (i.e., 6 dB).

There are different mechanisms (e.g., anatomical, neurophysiological) associated with TTS versus AUD INJ onset, making the relationship between these types of TS not completely direct. Nevertheless, the only data available for marine mammals, currently and likely in the future, will be from TTS studies (i.e., unlike for terrestrial mammals where direct measurements of AUD INJ exist). Thus, TTS represents the best information available from which AUD INJ onset can be estimated.

The criteria presented in Table 6 consist of both an acoustic threshold and auditory weighting function for the SEL_{24h} metric (auditory weighting functions are considered not appropriate for PK SPL metric).

[23] There has been one documented unexpected occurrence of PTS in a harbor seal that participated in multiple TTS studies (Reichmuth et al. 2019). Although these data are not suitable for directly deriving AUD INJ criteria, they provide a comparison to the resulting AUD INJ criteria value to actual PTS data.

[24] Similarly, for humans, NIOSH (1998) regards the range of audiometric testing variability to be approximately 5 dB.

Table 6: Summary of AUD INJ onset criteria.

	AUD INJ Onset Criteria* **(Received Level)** PLEASE SEE TABLE NOTES TO FULLY UNDERSTAND SYMBOLS MEANING	
Hearing Group	**Impulsive**	**Non-impulsive**
UNDERWATER		
Low-Frequency (LF) Cetaceans	*Cell 1* $L_{p,0\text{-pk,flat}}$: 222 dB $L_{E,p,\text{ LF,24h}}$: 183 dB	*Cell 2* $L_{E,p,\text{ LF,24h}}$: 197 dB
High-Frequency (HF) Cetaceans	*Cell 3* $L_{p,0\text{-pk,flat}}$: 230 dB $L_{E,p,\text{ HF,24h}}$: 193 dB	*Cell 4* $L_{E,p,\text{ HF,24h}}$: 201 dB
Very High-Frequency (VHF) Cetaceans	*Cell 5* $L_{p,0\text{-pk,flat}}$: 202 dB $L_{E,p,\text{VHF,24h}}$: 159 dB	*Cell 6* $L_{E,p,\text{ VHF,24h}}$: 181 dB
Phocid Pinnipeds (PW)	*Cell 7* $L_{p,0\text{-pk.flat}}$: 223 dB $L_{E,p,\text{PW,24h}}$: 183 dB	*Cell 8* $L_{E,p,\text{PW,24h}}$: 195 dB
Otariid Pinnipeds (OW)	*Cell 9* $L_{p,0\text{-pk,flat}}$: 230 dB $L_{E,p,\text{OW,24h}}$: 185 dB	*Cell 10* $L_{E,p,\text{OW,24h}}$: 199 dB
IN-AIR		
Phocid Pinnipeds (PA)	*Cell 11* $L_{p,0\text{-pk.flat}}$: 162 dB $L_{E,p,\text{PA,24h}}$: 140 dB	*Cell 12* $L_{E,p,\text{PA,24h}}$: 154 dB
Otariid Pinnipeds (OA)	*Cell 13* $L_{p,0\text{-pk,flat}}$: 177 dB $L_{E,p,\text{OA,24h}}$: 163 dB	*Cell 14* $L_{E,p,\text{OA,24h}}$: 177 dB

* Dual metric criteria for impulsive sounds: Use whichever criteria results in the larger isopleth for calculating AUD INJ onset. If a non-impulsive sound has the potential of exceeding the peak sound pressure level criteria associated with impulsive sounds, the PK SPL criteria are recommended for consideration for non-impulsive sources.

Note: Peak sound pressure level (Lp,0-pk) has a reference value of 1 µPa (underwater) and 20 µPa (in air), and weighted cumulative sound exposure level (LE,p) has a reference value of 1 µPa2s (underwater) and 20 µPa2s (in air). In this Table, criteria are abbreviated to be more reflective of International Organization for Standardization standards (ISO 2017; ISO 2020). The subscript "flat" is being included to indicate peak sound pressure are flat weighted or unweighted within the generalized hearing range of marine mammals underwater (i.e., 7 Hz to 165 kHz) or in air (i.e., 42 Hz to 52 kHz). The subscript associated with cumulative sound exposure level criteria indicates the designated marine mammal auditory weighting function (LF, HF, and VHF cetaceans, and PW, OW, PA, and OA pinnipeds) and that the recommended accumulation period is 24 hours. The weighted cumulative sound exposure level criteria could be exceeded in a multitude of ways (i.e., varying exposure levels and durations, duty cycle). When possible, it is valuable for action proponents to indicate the conditions under which these criteria will be exceeded.

2.3.1 Impulsive and Non-Impulsive Source Criteria

As with the previous Technical Guidance, this Updated Technical Guidance divides sources into impulsive and non-impulsive based on physical characteristics at the source, with impulsive sound having physical characteristics making them more injurious[25] (e.g., high peak sound

[25] Exposure to impulsive sounds more often leads to mechanical damage of the inner ear, as well as more complex patterns of hearing recovery (e.g., Henderson and Hamernik 1986; Hamernik and Hsueh 1991).

pressures and rapid rise times) than non-impulsive sound sources (terrestrial mammal data: Buck et al. 1984; Dunn et al. 1991; Hamernik et al. 1993; Clifford and Rogers 2009; marine mammal data: reviewed in Southall et al. 2007; Southall et al. 2019; and Finneran 2024 that appears as Appendix A of this Updated Technical Guidance).

The characteristics of the sound at a receiver, rather than at the source, are the relevant consideration for determining potential impacts. However, understanding these physical characteristics in a dynamic system with receivers moving over space and time is difficult. Nevertheless, it is known that as sound propagates from the source, the characteristics of impulsive sounds that make them more injurious start to dissipate due to effects of propagation (e.g., time dispersion/time spreading; Urick 1983; Sertlek et al. 2014; Martin et al. 2020[26]).

For the purposes of this Updated Technical Guidance,[27] sources are divided and defined as the following:

- Impulsive: produce sounds that are typically transient, brief (less than 1 second), broadband, and consist of high peak sound pressure with rapid rise time and rapid decay (ANSI 1986; NIOSH 1998; ANSI 2005).

- Non-impulsive: produce sounds that can be broadband, narrowband or tonal, brief or prolonged, continuous or intermittent) and typically do not have a high peak sound pressure with rapid rise/decay time that impulsive sounds do (ANSI 1995; NIOSH 1998).

Note: The term “impulsive” in this document relates specifically to NIHL and specifies the physical characteristics of an impulsive sound source, which likely gives them a higher potential to cause auditory TTS/AUD INJ. This definition captures how these sound types may be more likely to affect auditory physiology and is not meant to reflect categorizations associated with behavioral disturbance.

2.3.2 Metrics

2.3.2.1 Weighted Cumulative Sound Exposure Level (SEL_{24h}) Metric

The weighted SEL_{24h} metric takes into account both received level and duration of exposure (ANSI 2013), both factors that contribute to NIHL. Often this metric is normalized to a single sound exposure of one second[28]. NMFS intends for the weighted SEL_{24h} metric to account for the accumulated exposure (i.e., weighted SEL_{24h} cumulative exposure over the duration of the activity within a 24-h period).

The recommended application of the weighted SEL_{24h} metric is for individual activities/sources (e.g., See NMFS Optional User Spreadsheet Tool). It currently is not intended for accumulating sound exposure from multiple activities occurring within the same area or over the same time or to estimate the impacts of those exposures to an animal occurring over various spatial or temporal scales. Current data available for deriving criteria using this metric are based on exposure to only a single source and may not be appropriate for situations where exposure to

[26] NMFS is aware that this publication recommends the use of kurtosis to quantify the impulsiveness of a sound source.

[27] If these definitions are unclear, consult with NMFS. Further, NMFS is aware that one of the criticisms of these definitions is that they lack quantitative descriptions to define many of the key terms. NMFS also is aware that kurtosis might be a valuable metric to help move toward a quantitative means of defining whether a sound is impulsive or not. This is something that may be explored as more data become available and in reality, sounds likely fall along a continuum between impulsive and non-impulsive (Guan et al. 2022; Guan and Brookens 2023; Zeddies et al. 2023).

[28] While ANSI 1995 specifies a reference duration of one second, ISO 2017 indicates that the time duration be specified with this metric. Specifiyng the duration associated with is metric is essential, since it can be computed for a single signal or multiple signals. Note: this metric is referened to μPa^2s, while SPLs are referenced to μPa and are thus, not directly comparable.

multiple sources is occurring. As more data become available, the use of this metric can be re-evaluated, in terms of appropriateness, for application of exposure from multiple activities occurring in space and time. NMFS is open to exploring ways to better analyze multiple sound sources (simultaneous, concurrent, etc.), especially in terms of our optional User Spreadsheet Tool.

Equal Energy Hypothesis

One assumption made when applying the weighted SEL_{24h} metric is the equal energy hypothesis (EEH), where it is assumed that sounds of equal SEL_{24h} produce an equal risk for hearing loss (i.e., if the weighted SEL_{24h} of two sources are similar, a sound from a lower level source with a longer exposure duration may have similar risks compared to a shorter duration exposure from a higher level source). As has been shown to be the case with humans and terrestrial mammals (Henderson et al. 1991), the EEH does not always accurately describe all exposure situations for marine mammals due the inherent complexity of predicting TSs (e.g., Kastak et al. 2007; Mooney et al. 2009a; Mooney et al. 2009b; Finneran et al. 2010a; Finneran et al. 2010b; Finneran and Schlundt 2010; Kastelein et al. 2012b; Kastelein et al. 2013b; Kastelein et al. 2014a; Kastelein et al. 2014b; Popov et al. 2014; Finneran 2015; Kastelein et al. 2015b; Kastelein et al. 2016; von Benda-Beckmann et al. 2022).

Factors like sound level (e.g., overall level, sensation level, or level above background), duration, duty cycle (intermittent versus continuous exposure; potential recovery between intermittent periods), number of transient components (short duration and high amplitude), and/or frequency (especially in relation to hearing sensitivity) also are often important factors associated with TS (e.g., Buck et al. 1984; Clark et al. 1987; Ward 1991; Lataye and Campo 1996). This is especially the case for exposure to impulsive sound sources (Danielson et al. 1991; Henderson et al. 1991; Hamernik et al. 2003), which is why criteria in this Updated Technical Guidance are expressed as a PK SPL metric as well (see next section). However, in many cases the EEH approach functions reasonably well as a first-order approximation, especially for higher-level, short-duration sound exposures such as those that are most likely to result in TTS in marine mammals[29] (Finneran 2015). Additionally, no currently supported alternative method to accumulate exposure is available. If alternative methods become available, they can be evaluated and considered when the Updated Technical Guidance is updated.

Recommended Accumulation Period

To apply the weighted SEL_{24h} metric, a specified accumulation period is needed (i.e. 24-h). Generally, it is predicted that most receivers will minimize the amount of time they remain in the closest ranges to a sound source/activity. Exposures at the closest point of approach are the primary exposures contributing to a receiver's accumulated level (Gedamke et al. 2011). Additionally, several important factors determine the likelihood and duration overwhich a receiver is expected to be in close proximity to a sound source (i.e., overlap in space and time between the source and receiver). For example, accumulation time for fast moving (relative to the receiver) mobile sources is driven primarily by the characteristics of the source (i.e., speed, duty cycle). Conversely, for stationary sources, accumulation time is driven primarily by the characteristics of the receiver (i.e., swim speed and site fidelity associated with exposure period). NMFS recommends a maximum baseline accumulation period of 24 hours, but acknowledges that there may be specific exposure situations where this accumulation period requires adjustment (e.g., if activity lasts less than 24 hours or for situations where receivers are predicted to experience unusually long exposure durations[30]).

[29] When possible, it is valuable for action proponents to indicate the exposure conditions under which these criteria are likely to be exceeded.

[30] For example, where a resident population could be found in a small and/or confined area (Ferguson et al. 2015) and/or exposed to a long-duration activity with a loud sound source, or where a continuous stationery activity is nearby an area where marine mammals congregate, like a pinniped pupping beach.

After sound exposure ceases or between successive sound exposures, the potential for recovery from hearing loss exists, with AUD INJ resulting in incomplete recovery and TTS resulting in complete recovery. Predicting recovery from sound exposure can be complicated. Currently, recovery in wild marine mammals cannot be accurately quantified. However, Finneran et al. (2010a) and Finneran and Schlundt (2013) proposed a model that approximates recovery in bottlenose dolphins. The applicability of this model to other species and other exposure conditions has yet to be determined. For the Updated Technical Guidance's criteria, NMFS assumes for intermittent, repeated exposure that there is no recovery between subsequent exposures, although it has been demonstrated in terrestrial mammals (Clark et al. 1987; Ward 1991) and more recently in a marine mammal studies (Finneran et al. 2010b; Kastelein et al. 2014a; Kastelein et al. 2015b), that there is a reduction in damage and hearing loss with intermittent exposures.

Criteria in this Updated Technical Guidance (i.e., expressed as weighted SEL_{24h}) take into account the duration, as well as level (dB) of exposure. NMFS recognizes that accounting for duration of exposure, although supported by the scientific literature, adds a factor, as far as application of this metric to real-world activities.

NMFS does not provide specifications necessary to perform exposure modeling and relies on the action proponent to determine the model that best represents their activity. However, as an alternative option, NMFS provides a simple means of approximating exposure for action proponents that are unable to apply various factors into their model (See NMFS Optional User Spreadsheet Tool).

2.3.2.2 Peak Sound Pressure Level (PK SPL) Metric[31]

Sound exposure containing transient components (e.g., short duration and high amplitude; impulsive sounds) can create a greater risk of causing direct mechanical fatigue to the inner ear (as opposed to strictly metabolic) compared to sounds that are strictly non-impulsive (Henderson and Hamernik 1986; Levine et al. 1998; Henderson et al. 2008). Often the risk of damage from these transient components does not depend on the duration of exposure. This is the concept of "critical level," where damage switches from being primarily metabolic to more mechanical and the short duration of the impulse can be less than the ear's integration time, leading to the potential to damage beyond the level the ear can perceive (Akay 1978).

Human noise standards recognize and provide separate criteria for impulsive sound sources using the PK SPL metric (Occupational Safety and Health Administration (OSHA) 29 CFR 1910.95; Starck et al. 2003). Thus, weighted SEL_{24h} is not an appropriate metric to capture all the effects of impulsive sounds (i.e., it often violates EEH; NIOSH 1998), which is why instantaneous PK SPL has also been chosen as part of NMFS's dual metric criteria for impulsive sounds.[32] Auditory weighting is not considered appropriate with the PK SPL metric, as direct mechanical damage associated with sounds having high peak sound pressures typically does not strictly reflect the frequencies an individual species hears best (Ward 1962; Saunders et al. 1985; ANSI 1986; DoD 2004; OSHA 29 CFR 1910.95). Thus, this Updated Technical Guidance recommends that the PK SPL criteria be considered unweighted/flat-weighted within the generalized hearing range of marine mammals (i.e., 7 Hz to 165 kHz).

[31] Note: Do not confuse PK SPL with *maximum* RMS SPL (See Glossary).

[32] For non-impulsive sounds, the weighted SEL_{24h} criteria will likely result in the largest isopleth, compared to the PK SPL criteria. Thus, for the majority of non-impulsive sounds, the consideration of the PK SPL criteria is unnecessary. However, if a non-impulsive sound has the potential of exceeding the PK SPL criteria associated with impulsive sounds, NMFS recommends these PK SPL criteria be considered for non-impulsive sources (i.e., dual metrics). Publications on how to estimate PK SPL from SEL for seismic airguns and offshore impact pile drivers may be useful to action proponents (Galindo-Romero et al. 2015; Lippert et al. 2015).

2.3.3 Development of AUD INJ Onset Criteria

The development of the AUD INJ onset criteria consisted of the following procedure described in Finneran 2024 (Appendix A):

1. Methodology to derive marine mammal auditory weighting functions (described in more detail in Section 2.2.3 and Appendix A).

2. Identification and evaluation of currently available published data (Table 7) on hearing loss associated with sound exposure in marine mammals.
    - Because only published measurements exist on unexpected PTS in marine mammals (Reichmuth et al. 2019[33]), TTS onset measurements and associated criteria were evaluated and summarized to extrapolate to AUD INJ onset criteria.

    - Studies divided into the following categories:
        - Temporal Characteristics: Impulsive and Non-impulsive

        - Marine Mammal Hearing Groups: LF Cetaceans, HF Cetaceans, VHF Cetaceans, PW Pinnipeds, OW Pinniped, PA Pinnipeds, and OA Pinnipeds

3. Determination of TTS onset criteria by individual (RLs, in both PK SPL and SEL_{24h} metrics) based on methodology from Finneran 2024 for impulsive and non-impulsive sounds (Full detail in Appendix A).

    - Non-impulsive sounds:
        - Only TTS data from behavioral studies were used, since studies using AEP methodology typically result in larger thresholds shifts (e.g., up to 10 dB difference, Finneran et al. 2007a) and are considered to be non-representative (as illustrated in Appendix A).

        - TTS onset derived on a per individual basis by combining available data to create a single TTS growth curve (e.g., dB TTS/dB noise) by frequency as a function of $SEL_{24h.}$

Table 7: Available underwater and in-air marine mammal threshold shift studies.

References in Chronological Order (new references added for Updated Technical Guidance are in italics)	**Sound Source (sound source category)**	**Species (number of individuals^, hearing group)**
UNDERWATER		
Kastak et al. 1999	Octave-band noise (non-impulsive)	California sea lion (1, OW); northern elephant seal (1, PW); harbor seal (1, PW)
Finneran et al. 2000	Explosion simulator (impulsive)*	Bottlenose dolphin (2, HF); beluga (1, HF)
Schlundt et al. 2000	Tones (non-impulsive)	Bottlenose dolphin (5, HF); beluga (2, HF)
Finneran et al. 2002	Seismic watergun (impulsive)	Bottlenose dolphin (1, HF); beluga (1, HF)

[33] Reichmuth et al. 2019 reported a PTS of 8 dB at 5.8 kHz in a harbor seal (PW) after exposure to a 4.1 kHz tone with cumulative SEL exposure of 199 dB (unweighted). Although these data are not suitable for directly deriving AUD INJ criteria, they provide an opportunity to compare the resulting AUD INJ criteria value to actual PTS data. Note: The PTS onset criteria for PW pinnipeds is lower than the level (195 dB $SEL_{24h)}$ that resulted in PTS in Reichmuth et al. 2019.

References in Chronological Order (new references added for Updated Technical Guidance are in italics)	**Sound Source (sound source category)**	**Species (number of individuals^, hearing group)**
Finneran et al. 2003	Arc-gap transducer (impulsive)*	California sea lion (2, OW)
Nachtigall et al. 2003	Octave-band noise (non-impulsive)	Bottlenose dolphin (1, HF)
Nachtigall et al. 2004	Octave-band noise (non-impulsive)	Bottlenose dolphin (1, HF)
Finneran et al. 2005a	Tones (non-impulsive)	Bottlenose dolphin (2, HF)
Kastak et al. 2005	Octave-band noise (non-impulsive)	California sea lion (1, OW); northern elephant seal (1, PW); harbor seal (1, PW)
Finneran et al. 2007a	Tones (non-impulsive)	Bottlenose dolphin (1, HF)
Lucke et al. 2009	Single airgun (impulsive)	Harbor porpoise (1, VHF)
Mooney et al. 2009a	Octave-band noise (non-impulsive)	Bottlenose dolphin (1, HF)
Mooney et al. 2009b	Mid-frequency sonar (non-impulsive)	Bottlenose dolphin (1, HF)
Finneran et al. 2010a	Tones (non-impulsive)	Bottlenose dolphin (2, HF)
Finneran et al. 2010b	Tones (non-impulsive)	Bottlenose dolphin (1, HF)
Finneran and Schlundt 2010	Tones (non-impulsive)	Bottlenose dolphin (1, HF)
Popov et al. 2011a	½ octave band noise (non-impulsive)	Yangtze finless porpoise (2, VHF)
Popov et al. 2011b	½ octave band noise (non-impulsive)	Beluga (1, HF)
Kastelein et al. 2012a	Octave-band noise (non-impulsive)	Harbor seal (2, PW)
Kastelein et al. 2012b	Octave-band noise (non-impulsive)	Harbor porpoise (1, VHF)
Finneran and Schlundt 2013	Tones (non-impulsive)	Bottlenose dolphin (2, HF)
Popov et al. 2013	½ -octave band noise (non-impulsive)	Beluga (2, HF)
Kastelein et al. 2013a	Octave-band noise (non-impulsive)	Harbor seal (1, PW)
Kastelein et al. 2013b	Tone (non-impulsive)	Harbor porpoise (1, VHF)
Popov et al. 2014	½ octave band noise (non-impulsive)	Beluga (2, HF)
Kastelein et al. 2014a	1-2 kHz sonar (non-impulsive)	Harbor porpoise (1, VHF)
Kastelein et al. 2014b	6.5 kHz tone (non-impulsive)	Harbor porpoise (1, VHF)
Kastelein et al. 2015a	Impact pile driving (impulsive)*	Harbor porpoise (1, VHF)
Kastelein et al. 2015b	6-7 kHz sweeps (non-impulsive)	Harbor porpoise (1, VHF)
Finneran et al. 2015	Single airgun producing multiple shots (impulsive)*	Bottlenose dolphin (3, HF)
Popov et al. 2015	½ octave band noise (non-impulsive)	Beluga (1, HF)
Kastelein et al. 2016	Impact pile driving (impulsive)*	Harbor porpoise (2, VHF)

References in Chronological Order (new references added for Updated Technical Guidance are in italics)	Sound Source (sound source category)	Species (number of individuals^, hearing group)
Reichmuth et al. 2016	Single airgun (impulsive)*	Ringed seals (2, PW); Spotted seals (2, PW)
Popov et al. 2017	½ octave band noise (non-impulsive)	Beluga (1, HF)
Kastelein et al. 2017b	Simultaneous airguns producing multiple shots (impulsive)*	Harbor porpoise (1, VHF)
Kastelein et al. 2017c	3.5-4.1 kHz sonar (non-impulsive)	Harbor porpoise (2, VHF)
Kastelein et al. 2018	Impact pile driving (impulsive)*	Harbor seal (2, PW)
Kastelein et al. 2019a	6.5 kHz tone (non-impulsive)	Harbor seal (2, PW)
Kastelein et al. 2019b	1/6 octave noise at 16 kHz (non-impulsive)	Harbor porpoise (2)
Kastelein et al. 2019c	1/6 octave noise at 32 kHz (non-impulsive)	Harbor porpoise (2, VHF)
Reichmuth et al. 2019	4.1 kHz tone (non-impulsive)⁺	Harbor seal (1, PW)
Kastelein et al. 2019d	1/6 octave noise at 16 kHz (non-impulsive)	Harbor seal (2, PW)
Schaffeld et al. 2019	Artificial ADD with peak at 14 kHz (non-impulsive)	Harbor porpoise (1, VHF)
Kastelein et al. 2020a	1/6 octave noise at 63 kHz (non-impulsive)	Harbor porpoise (2, VHF)
Kastelein et al. 2020b	1/6 octave noise at 32 kHz (non-impulsive)	Harbor seal (2. PW)
Kastelein et al. 2020c	1/6 octave noise at 40 kHz (non-impulsive)	Harbor seal (2, PW)
Kastelein et al. 2020d	1/6 octave noise at 88.4 kHz (non-impulsive)	Harbor porpoise (1, VHF)
Kastelein et al. 2020e	1/6 octave noise at 1.5 kHz and 6.5 kHz (non-impulsive)	Harbor porpoise (1, VHF)
Kastelein et al. 2020f	Simultaneous airguns producing multiple shots (impulsive)*	Harbor porpoise (1, VHF)
Kastelein et al. 2020g	1/6 octave noise at 0.5, 1, and 2 kHz (non-impulsive)	Harbor seal (2, PW)
Sills et al. 2020b	Single airgun producing single and multiple shots (impulsive)	Bearded seal (1, PW)
Kastelein et al. 2021a	1/6 octave noise at 0.5 (non-impulsive)	Harbor porpoise (1, VHF)
Kastelein et al. 2021b	1/6 octave noise at 2 and 4 kHz (non-impulsive)	California sea lion (2, OW)
Kastelein et al. 2022a	1/6 octave noise at 8 and 16 kHz (non-impulsive)	California sea lion (2, OW)
Kastelein et al. 2022b	1/6 octave noise at 0.6 and 1 kHz (non-impulsive)	California sea lion (2, OW)
Schaffeld et al. 2022	28 kHz acoustic flowmeter ping (non-impulsive)	Harbor porpoise (1, VHF)
Finneran et al. 2023a	Tones (non-impulsive)	Bottlenose dolphin (2, HF)
Kastelein et al. 2024 (in prep)	1/6 octave noise at 32 and 40 kHz (non-impulsive)	California sea lion (2, OW)
Mulsow et al. 2023	Narrowband (1/6-octave), 10-ms noisebursts at 8 kHz	Bottlenose dolphin (3, HF)

References in Chronological Order (new references added for Updated Technical Guidance are in italics)	Sound Source (sound source category)	Species (number of individuals^, hearing group)
	(impulsive)	
IN-AIR		
Kastak et al. 2007	Octave-band noise (non-impulsive)	California sea lion (1, OA)
Reichmuth et al. 2024 (in prep)	Octave-band noise (non-impulsive)	Harbor seal (1, PA)

^Note: Some individuals have been used in multiple studies.
*No incidents of temporary threshold shift were recorded in study.
+PTS was reported in this study, as a result of repeated TTS.

- TTS onset was defined as the SEL_{24h} value from the growth curve interpolated at a value of TTS = 6 dB. Only datasets where data were available with a threshold shift (TS) above and below 6 dB were used to define TTS onset (i.e., extrapolation was not performed on datasets not meeting this criterion).

- Interpolation was used to estimate SEL_{cum} necessary to induce 6 dB of TTS by hearing group (Appendix A, Figure A9). The mean SEL_{24} for TTS onset was then computed at each frequency for which more than one data point existed. Finally, some mean TTS onset data points for groups VHF cetaceans and PW pinnipeds (represented with an open circle in Fig. A10) were excluded from the fitting process. This was done as a precautionary measure, where new data indicate higher TTS onset values than those predicted by the previous version of the Technical Guidance.

- Finally, weighted criteria for TTS onset were determined by the minimum value of the auditory exposure function (Equation 2), which is mathematically equivalent to $K + C$ (Table 8).

Table 8: TTS onset criteria for non-impulsive sounds.

Hearing Group	C (dB)	K (dB)	Weighted TTS onset acoustic criteria (SEL_{24h})*
UNDERWATER			
Low-frequency (LF) cetaceans	0.12	177	177 dB
High-frequency (HF) cetaceans	0.32	181	181 dB
Very High-frequency (VHF) cetaceans	0.91	160	161 dB
Phocid pinnipeds (PW)	0.29	175	175 dB
Otariid pinnipeds (OW)	1.37	178	179 dB
IN-AIR			
Phocid pinnipeds (PA)	0.83	133	134 dB
Otariid pinnipeds (OA)	1.18	156	157 dB

* Determined from minimum value of auditory exposure function and the weighting function at its peak (i.e., mathematically equivalent to $K + C$).

- Impulsive sounds:
  - Available TTS data for impulsive sources were weighted based on auditory weighting functions for the appropriate hearing group (HF cetaceans, VHF cetaceans, and PW pinnipeds: Finneran et al. 2002; Lucke et al. 2009; Sills et al. 2020b; Mulsow et al. 2023).

  - For hearing groups, where impulsive TTS onset data did not exist, Finneran (2023) derived impulsive TTS onset criteria using the relationship between non-impulsive TTS onset criteria and impulsive TTS onset criteria for HF cetaceans, VHF cetaceans, and PW pinnipeds (i.e., similar to what was presented in previous version of the Technical Guidance). Using the mean of these data resulted in an 9.2 dB relationship, which was used as a surrogate for the other hearing groups (i.e., non-impulsive TTS criteria was 9.2 dB higher than impulsive TTS criteria).

  - To estimate PK onset criteria, dynamic range methodology[34] was used (as with the previous Technical Guidance). The dynamic range methodology was defined as the difference (in dB) between the impulsive noise, PK TTS onset and the hearing threshold at f_0 for hearing groups for which data are available (HF and VHF cetaceans). For HF and VHF cetaceans, the dynamic ranges are 173 and 147 dB, respectively (mean, median = 160 dB). Therefore, for the remaining hearing groups, the PK TTS criteria were estimated by adding 160 dB to the hearing threshold at f_0.

4. Extrapolation for AUD INJ onset criteria (in both PK SPL and SEL metrics) based on data from humans and terrestrial mammals, with the assumption that the mechanisms associated with noise-induced TS in marine mammals is similar, if not identical, to that recorded in terrestrial mammals.

- Non-impulsive sounds:
  - AUD INJ onset criteria were estimated using TTS growth rates based on those marine mammal studies where 20 dB or more of a TS was induced. This was done to estimate more accurately AUD INJ onset, since using growth rates based on smaller TS are often shallower compared to those inducing greater TS (See Appendix A.3).

  - AUD INJ onset was derived using the same methodology as TTS onset, with AUD INJ onset defined as the SEL_{24h} value from the fitted curve at a TTS of 40 dB.

  - Offset between TTS and AUD INJ onset criteria were examined and ranged from 9 to 52 dB (mean/median: 23/17 dB from available cetacean and pinniped data, n=12). Thus, based on these data, a conservative 20 dB offset was chosen to estimate AUD INJ onset criteria from TTS onset criteria for non-impulsive sources (i.e., 20 dB was added to K to determine AUD INJ onset, assuming the shape of the AUD INJ auditory exposure function is identical to the TTS auditory exposure function for that hearing group).

[34] Dynamic range is used in human noise standards to define the PK SPL acoustic criteria for impulsive sounds (e.g., 140 dB from OSHA 29 CFR 1910.95). For the purposes of this Updated Technical Guidance, the intent is to relate the threshold of audibility and TTS onset level, not the threshold of pain, as dynamic range is typically defined (Yost 2007).

- Impulsive sounds: Based on limited available marine mammal impulsive data, the relationships previously derived in Southall et al. (2007, 2019; and used in previous version of the Technical Guidance), which relied upon terrestrial mammal growth rates (Henderson and Hamernik 1982; Henderson and Hamernik 1986; Price and Wansack 1989; Levine et al. 1998; Henderson et al. 2008), was used to predict AUD INJ onset:

  - Resulting in an approximate 15 dB difference between TTS and AUD INJ onset criteria in the SEL_{24h} metric.

  - Southall et al. (2007; 2019) recommended a 6 dB of TTS/dB of noise growth rate for PK SPL criteria. This recommendation was based on several factors, including ensuring that the PK SPL criteria did not unrealistically exceed the cavitation threshold of water. Resulting in an approximate 6 dB difference between TTS and AUD INJ onset criteria in the PK SPL metric.

III. UPDATING ACOUSTIC TECHNICAL GUIDANCE AND CRITERIA

Research on the effects of anthropogenic sound on marine mammals has increased dramatically in the last decade, as seen by the additional data available for this Updated Technical Guidance versus the previous version and will likely continue to increase in the future. As recommended (Tougaard et al. 2022), the Updated Technical Guidance will be reviewed periodically and updated as appropriate to reflect the compilation, interpretation, and synthesis of the scientific literature.

NMFS's initial approach for updating current criteria for protected marine species consisted of providing criteria for underwater and in-air AUD INJ onset for marine mammals via this document. As more data become available, technical guidance may be established for additional protected marine species, such as sea turtles and marine fishes. As with this document, public review and outside peer review will be integral to the process.

3.1 PROCEDURE AND TIMELINE FOR FUTURE UPDATES TO THE TECHNICAL GUIDANCE

NMFS will continue to monitor and evaluate new data as they become available and periodically convene staff from our various offices, regions, and science centers to revise the Updated Technical Guidance as appropriate (anticipating updates to occur on a three to five year cycle). In addition to evaluating new, relevant scientific studies, NMFS will also periodically re-examine basic concepts and definitions (e.g., hearing groups, AUD INJ and TTS, auditory weighting functions, impulsive/non-impulsive), appropriate metrics, temporal and spatial considerations, and other relevant topics. Updates will be posted at: https://www.fisheries.noaa.gov/national/marine-mammal-protection/marine-mammal-acoustic-technical-guidance.

Since the methodology for deriving composite audiograms and associated marine mammal auditory weighting functions, as well as AUD INJ and TTS criteria are data driven, any new information that becomes available has the potential to cause some amount of change for that specific hearing group but also other hearing groups, if they rely on surrogate data. It may not be feasible to make changes every time a new data point becomes available. Instead, NMFS will periodically examine new data and consider the impacts of those studies on the Updated Technical Guidance to determine what and when revisions/updates may be appropriate. At the same time, there may be special circumstances that merit evaluation of data on a more accelerated timeline (e.g., LF cetacean data that could result in significant changes to the current Updated Technical Guidance[35]).

[35] NMFS is aware that the National Marine Mammal Foundation successfully collected preliminary hearing data on two minke whales during their third field season (2023) in Norway. These data have implications for not only the generalized hearing range for low-frequency cetaceans but also on their weighting function. However, at this time, no official results have been published. Furthermore, a fourth field season (2024) is proposed, where more data will likely be collected. Thus, it is premature for us to propose any changes to our current Updated Technical Guidance. However, mysticete hearing data is identified as a special circumstance that could merit re-evaluating the acoustic criteria in this document. Therefore, we anticipate that once the data from both field seasons are published, it will likely necessitate updating this document (i.e., likely after the data gathered in the summer 2024 field season and associated analysis are published).

APPENDIX A: FINNERAN TECHNICAL REPORT

The Finneran Technical Report (Finneran 2024), regarding methodology for deriving auditory weighting functions and thresholds for marine mammal species, is included for reference in Appendix A. NMFS has modified the contents of the Finneran Technical Report to reflect the marine mammal hearing groups depicted in our Updated Technical Guidance (main document), other than not removing reference to Sirenans (SI), which do not fall under NMFS's jurisdiction. Additionally, NMFS has added "A" before Figures and Tables to denote Appendix A and be consistent with the other appendices in the Updated Technical Guidance.

Some of the abbreviations within this Appendix may not reflect those used elsewhere in the Updated Technical Guidance. The following provides some "translations":

Term	Updated Technical Guidance	Appendix A
Auditory injury	AUD INJ	INJ
Otariid pinnipeds in-air	OA	OCA
Otariid pinnipeds in water	OW	OCW
Phocid pinnipeds in-air	PA	PCA
Phocid pinnipeds underwater	PW	PCW
Peak sound pressure level	PK SPL	Peak SPL
Cumulative sound exposure level	SEL_{24h}	SEL

Note:

- Literature cited in this section are included at the end of this Appendix (i.e., not all references found in this Appendix are included in the Literature Cited for the Updated Technical Guidance).

- Additionally, terminology, symbols, and abbreviations used in this appendix may not match those used elsewhere in the Updated Technical Guidance.

- Finally, this document includes criteria for species that are not under NMFS's jurisdiction (e.g., walrus, polar bears, manatees, dugongs, sea otters).

Marine mammal auditory weighting functions and exposure functions for US Navy Phase 4 acoustic effects analyses

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NIWC Pacific

26 FEB 2024

EXECUTIVE SUMMARY

The US Navy conducts acoustic effects analyses to estimate the potential effects of Navy activities that introduce high-levels of sound or explosive energy into the marine environment. Acoustic effects analyses begin with mathematical modeling to predict the sound transmission patterns from Navy sources. These data are then coupled with marine species distribution and abundance data to determine the sound levels likely to be received by various marine species. Finally, received exposure levels are compared to acoustic impact criteria and thresholds to estimate the specific effects that animals exposed to Navy-generated sound may experience. This document describes the rationale and steps used to define criteria and numeric thresholds for predicting auditory effects on marine mammals exposed to non-impulsive acoustic sources (e.g., sonars and other active acoustic sources) and impulsive sources (e.g., explosives, pile driving, and air guns). Previous development of Navy acoustic impact criteria and thresholds occurred as part of Phase 2 (c. 2012) and Phase 3 (c. 2015) of the Navy's Tactical Training Theater Assessment and Planning (TAP) Program. To remain consistent with prior terminology, the present criteria and thresholds are referred to as the "Phase 4" criteria and thresholds. Since the derivation of Phase 3 acoustic criteria and thresholds, new data have been obtained related to the effects of noise on marine mammal hearing. Therefore, for Phase 4, new criteria and thresholds for the onset of temporary hearing loss and the onset of auditory injury were developed utilizing all relevant, available data.

Marine mammals were divided into eight groups for analysis: low-frequency cetaceans (group LF: mysticetes), high-frequency cetaceans (group HF: delphinids, monodonts, beaked whales, sperm whales), very high-frequency cetaceans (group VHF: phocoenids, river dolphins, pygmy/dwarf sperm whales), sirenians (group SI: manatees and dugongs), phocid carnivores in water and in air (groups PCW and PCA, respectively: true seals), and otariids and other non-phocid marine carnivores in water and air (groups OCW and OCA, respectively: sea lions, fur seals, walruses, sea otters, polar bears).

For each group, a frequency-dependent weighting function and numeric thresholds for the onset of temporary threshold shift (TTS) and the onset of auditory injury (INJ) were estimated. The onset of TTS is defined as a TTS of 6 dB measured approximately 2–5 min after exposure. A TTS of 40 dB is used as a proxy for the onset of auditory injury; i.e., it is assumed that exposures beyond those capable of causing 40 dB of TTS have the potential to result in permanent threshold shift (PTS) or other auditory injury (e.g., loss of cochlear neuron synapses, even in the absence of PTS). Exposures just sufficient to cause TTS or INJ are denoted as "TTS onset" or "INJ onset" exposures. Onset levels are treated as step functions or "all-or-nothing" thresholds: exposures above the TTS or INJ onset level are assumed to always result in TTS or INJ, while exposures below the TTS or INJ onset level are assumed to not cause TTS or INJ. For non-impulsive exposures, onset levels are specified in frequency-weighted sound exposure level (SEL); for impulsive exposures, dual metrics of weighted SEL and unweighted peak sound pressure level (PK) are used.

Weighting function amplitudes (Fig. A.E-1) are specified using Eq. (E-1). Tables A.E-1 and A.E-2 summarize the parameters necessary to calculate the weighting function amplitudes and the weighted threshold values, respectively.

$$W(f) = C + 10\log_{10}\left\{\frac{(f/f_1)^{2a}}{\left[1+(f/f_1)^2\right]^a\left[1+(f/f_2)^2\right]^b}\right\} \qquad \text{(E-1)}$$

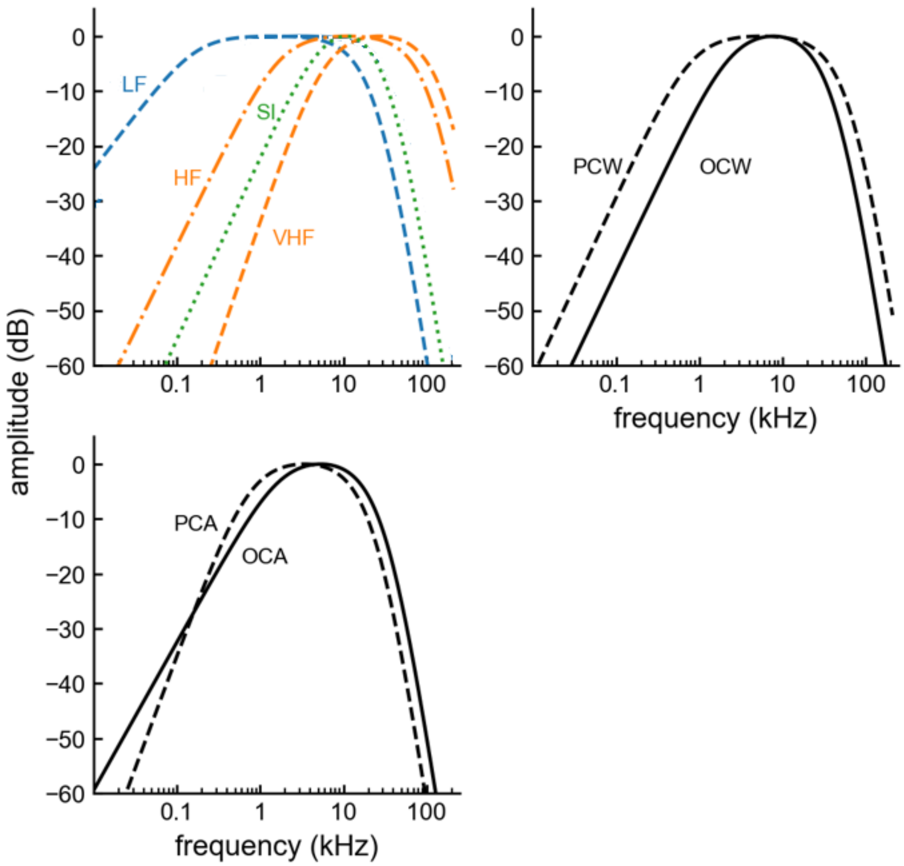

Figure A.E-1. Navy Phase 4 weighting functions for all species groups. Parameters required to generate the functions are provided in Table A.E-1.

Table A.E-1. Summary of function parameters for use in Eqs. (A.E-1) and (A.E-2) to generate Phase 4 weighting functions and exposure functions, respectively.

Group	a	b	f_1 (kHz)	f_2 (kHz)	C (dB)	Non-impulse K_{TTS} (dB)	Non-impulse K_{INJ} (dB)	Impulse K_{TTS} (dB)	Impulse K_{INJ} (dB)
LF	0.990	5.00	0.168	26.6	0.120	177	197	168	183
HF	1.55	5.00	1.73	129	0.320	181	201	177	192
VHF	2.23	5.00	5.93	186	0.910	160	180	143	158
OCW	1.58	5.00	2.53	43.8	1.37	178	198	168	183
PCW	1.63	5.00	0.810	68.3	0.290	175	195	168	183
SI	1.66	5.00	5.91	37.6	3.61	176	196	167	182
OCA	1.35	5.00	1.75	32.5	1.18	156	176	147	162
PCA	2.05	5.00	0.739	24.4	0.830	133	153	124	139

Table A.E-2. Summary of Phase 4 TTS/INJ thresholds*. SEL thresholds are in dB re 1 μPa²s underwater and dB re (20 μPa)²s in air (groups OCA and PCA only). Peak SPL thresholds are in dB re 1 μPa underwater and dB re 20 μPa in air (groups OCA and PCA only).

Group	Non-impulsive TTS threshold SEL (weighted)	Non-impulsive INJ threshold SEL (weighted)	Impulsive TTS threshold SEL (weighted)	Impulsive TTS threshold peak SPL (unweighted)	Impulsive INJ threshold SEL (weighted)	Impulsive INJ threshold peak SPL (unweighted)
LF	177	197	168	216	183	222
HF	181	201	178	224	193	230
VHF	161	181	144	196	159	202
OCW	179	199	170	224	185	230
PCW	175	195	168	217	183	223
SI	180	200	171	219	186	225
OCA	157	177	148	171	163	177
PCA	134	154	125	156	140	162

* **NMFS added footnote**: Thresholds are determined from minimum value of auditory exposure function and the weighting function at its peak (i.e., mathematically equivalent to $K + C$) in Table A-8. However, it should be noted that only rounded values are presented in this Table, so for HFC and OCW, impulsive SEL thresholds do not appear to equal $K + C$, but in actuality, they do..

To compare Phase 4 weighting functions and TTS/INJ SEL thresholds to those used in Phase 3, both the weighting function shape and the weighted threshold values must be considered; the weighted thresholds by themselves only indicate the TTS/INJ threshold at the most susceptible frequency (based on the relevant weighting function). In contrast, the TTS/INJ *exposure functions* incorporate both the shape of the weighting function and the weighted threshold value and provide the best means of comparing the frequency-dependent TTS/INJ thresholds for Phase 3 and 4. Exposure functions are defined using Eq. (E-2).

$$E(f) = K - 10\log_{10}\left\{\frac{(f/f_1)^{2a}}{\left[1+(f/f_1)^2\right]^a\left[1+(f/f_2)^2\right]^b}\right\} \tag{E-2}$$

Figures A.E-2 and A.E-3 compare the TTS/INJ exposure functions for non-impulsive sounds (e.g., sonars) and impulsive sounds (e.g., explosions), respectively, used in Phase 3 and Phase 4. Figures A.E-4 and A.E-5 compare exposure functions across species groups, for non-impulsive and impulsive exposures, respectively. Table A.E-3 compares the Phase 3 and 4 (unweighted) peak SPL thresholds for impulsive sounds.

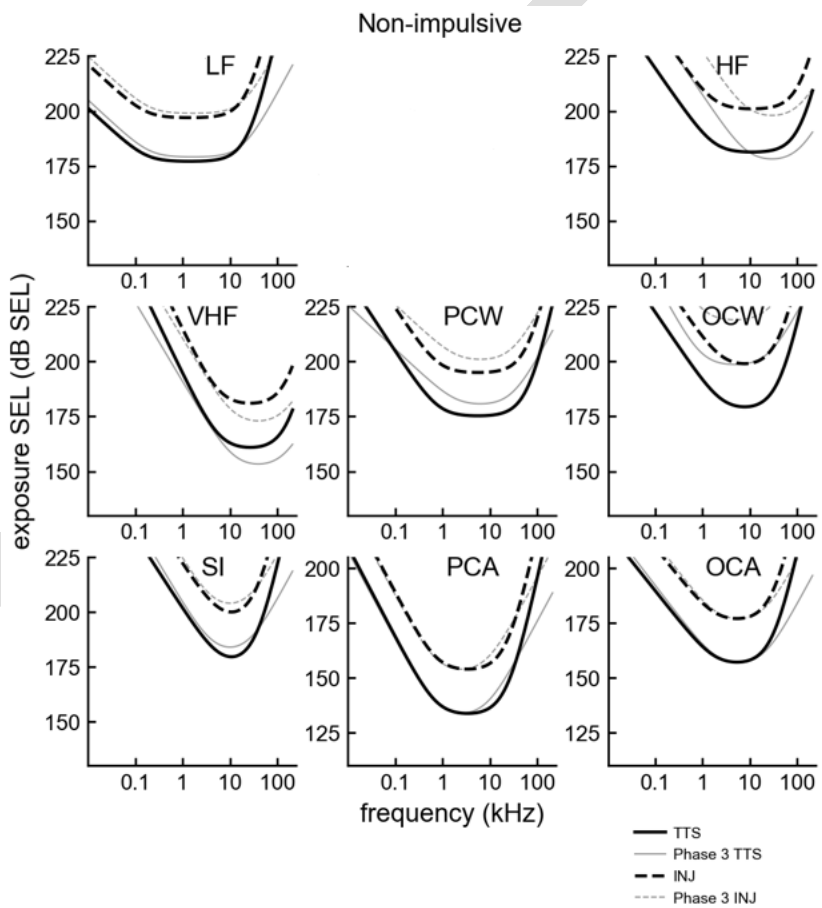

Figure A.E-2. TTS and INJ exposure functions for sonars and other (non-impulsive) active acoustic sources. Heavy solid lines — Navy Phase 4 TTS exposure functions (Table A.E-1). Thin solid lines — Navy Phase 3 TTS exposure functions. Heavy dashed lines — Navy Phase 4 INJ exposure functions (Table A.E-1). Thin dashed lines — Navy Phase 3 INJ exposure functions.

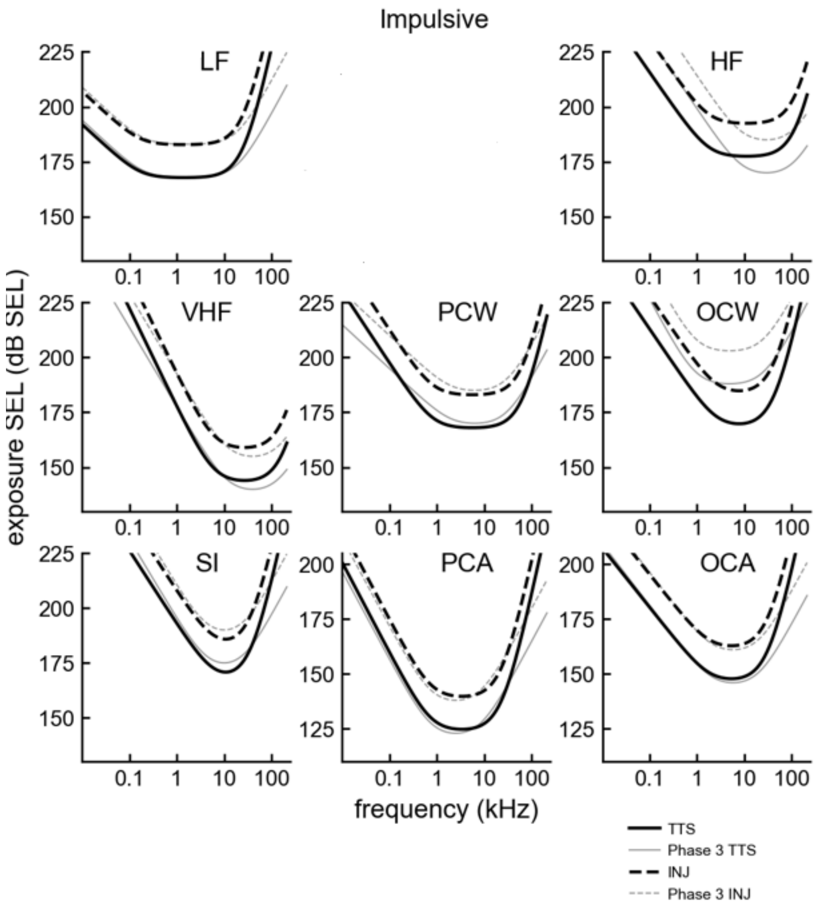

Figure A.E-3. TTS and INJ exposure functions for explosives, impact pile driving, air guns, and other impulsive sources. Heavy solid lines — Navy Phase 4 TTS exposure functions (Table A.E-1). Thin solid lines — Navy Phase 3 TTS exposure functions. Heavy dashed lines — Navy Phase 4 INJ exposure functions (Table A.E-1). Thin dashed lines — Navy Phase 3 INJ exposure functions.

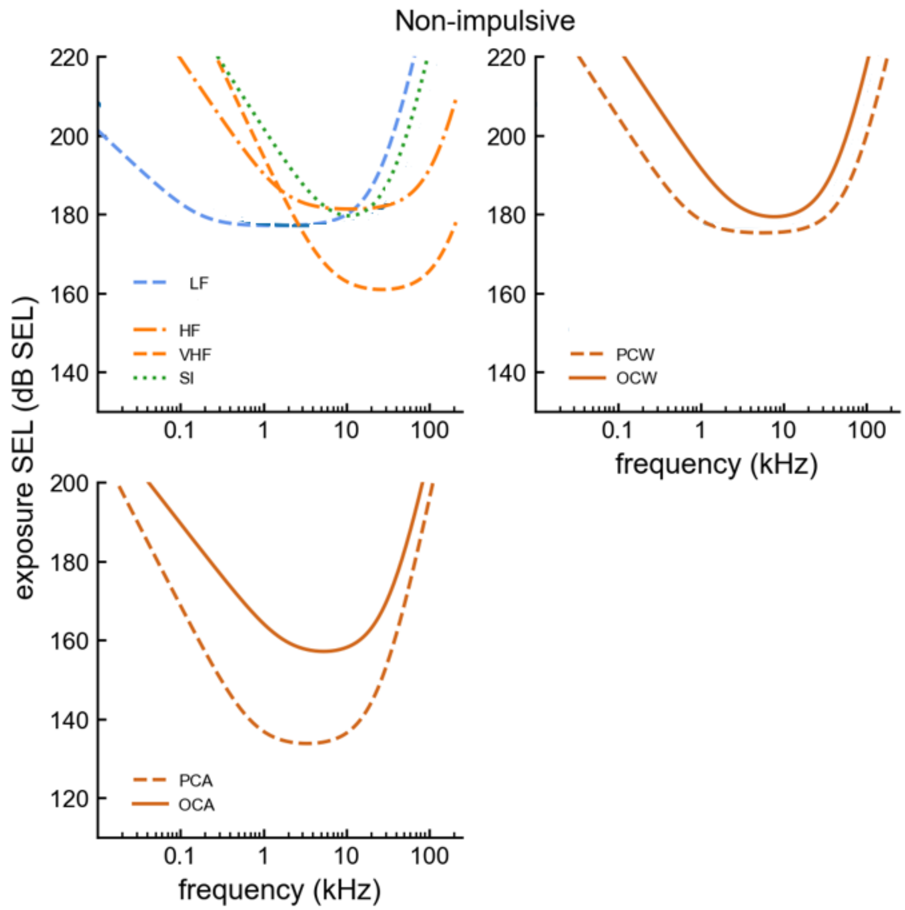

Figure A.E-4. Comparison of Navy Phase 4 TTS exposure functions for sonars and other (non-impulsive) active acoustic sources across species groups.

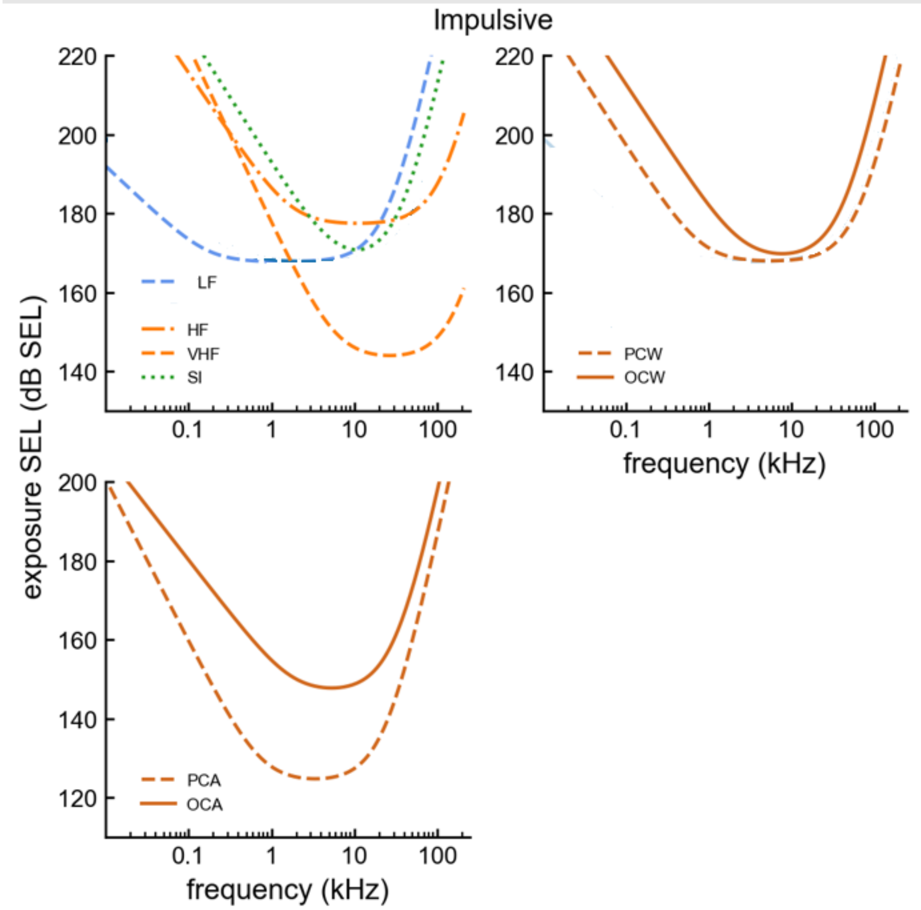

Figure A.E-5. Comparison of Navy Phase 4 TTS exposure functions for explosives, impact pile driving, air guns, and other impulsive sources across species groups.

Table A.E-3. Comparison of Phase 3 and Phase 4 TTS/INJ peak SPL thresholds for explosives, impact pile driving, air guns, and other impulsive sources. Peak SPL thresholds are in dB re 1 µPa underwater and dB re 20 µPa in air (groups OCA and PCA only).

Group	TTS Phase 3	TTS Phase 4	INJ Phase 3	INJ Phase 4
LF	213	216	219	222
HF	224	224	230	230
VHF	196	196	202	202
OCW	226	224	232	230
PCW	212	217	218	223
SI	220	219	226	225
OCA	170	171	176	177
PCA	155	156	161	162

The most significant differences between the Phase 3 and Phase 4 functions and thresholds include the following:

(1) Group names were changed from Phase 3 to be consistent with Southall et al. (2019). Specifically, the Phase 3 mid-frequency (MF) cetacean group is now designated as the high-frequency (HF) cetacean group, and the group previously designated as high-frequency (HF) cetaceans is now the very-high frequency (VHF) cetacean group.

(2) For the HF group, Phase 4 onset TTS/INJ thresholds are lower compared to Phase 3 at frequencies below ~10 kHz. This is a result of new TTS onset data for dolphins at low frequencies (Finneran et al., 2022).

(3) For the PCW group, new TTS data for harbor seals (Kastelein et al., 2020b; Kastelein et al., 2020f) resulted in slightly lower TTS/INJ thresholds at high-frequencies compared to Phase 3.

(4) For group OCW, new TTS data for California sea lions (Kastelein et al., 2021b; Kastelein et al., 2022b, a) resulted in significantly lower TTS/INJ thresholds compared to Phase 3.

1. INTRODUCTION

1.1. OVERVIEW

The US Navy conducts acoustic effects analyses to estimate the potential effects of Navy training and testing activities that introduce high-levels of sound or explosive energy into the marine environment. Acoustic effects analyses begin with mathematical modeling to predict the sound transmission patterns from Navy sources. These data are then coupled with marine species distribution and abundance data to determine sound levels likely to be received by various marine species. Finally, acoustic impact criteria and thresholds are applied to estimate the specific effects that animals exposed to Navy-generated sound may experience.

This document describes the rationale and steps used to define numeric thresholds for predicting auditory effects on marine mammals exposed to active sonars, other (non-impulsive) active acoustic sources, explosives, pile driving, air guns, and other impulsive acoustic sources for Navy acoustic effects analyses. Previous development of Navy acoustic impact criteria and thresholds occurred as part of Phase 2 (c. 2012) and Phase 3 (c. 2015) of the Navy's Tactical Training Theater Assessment and Planning (TAP) Program. To remain consistent with prior terminology, the present criteria and thresholds are referred to as the "Phase 4" criteria and thresholds.

1.2. IMPULSE VERSUS. NON-IMPULSIVE NOISE

When analyzing the auditory effects of noise exposure, it is often helpful to broadly categorize noise as either impulsive noise — noise with high peak sound pressure, short duration, and fast rise-time — or non-impulsive (i.e., steady-state) noise. When considering auditory effects, sonars, other coherent active sources, and vibratory pile driving are considered to be non-impulsive sources, while explosives, impact pile driving, and air guns are treated as impulsive sources. Note that the terms non-impulsive or steady-state do not necessarily imply long duration signals, only that the acoustic signal has sufficient duration to overcome starting transients and reach a steady-state condition.

1.3. NOISE-INDUCED THRESHOLD SHIFTS AND AUDITORY INJURY

Exposure to sound with sufficient duration and sound pressure level (SPL) may result in an elevated hearing threshold (i.e., a loss of hearing sensitivity), called a noise-induced threshold shift (NITS). If the hearing threshold eventually returns to normal, the NITS is called a temporary threshold shift (TTS); otherwise, if thresholds remain elevated after some extended period of time, the remaining NITS is called a permanent threshold shift (PTS).

A variety of terrestrial and marine mammal data sources (e.g., Ward et al., 1958; Ward et al., 1959; Ward, 1960; Miller et al., 1963; Kryter et al., 1966; Finneran et al., 2007; Kastelein et al., 2013a) indicate that NITSs up to 40 to 50 dB, measured a few minutes after exposure, may be induced without PTS. Therefore, an exposure producing an initial TTS of 40 dB can be considered a conservative upper limit for reversibility and any additional exposure could result in some PTS. This means that 40 dB of TTS, measured a few minutes after exposure, can be used as a conservative estimate for the onset of PTS.

In some cases, intense noise exposures have caused auditory injury (INJ, e.g., loss of cochlear neuron synapses), despite thresholds eventually returning to normal; i.e., it is possible to have INJ without a resulting PTS (e.g., Kujawa and Liberman, 2006, 2009; Kujawa, 2010; Fernandez et al., 2015; Ryan et al., 2016; Houser, 2021). In these situations, however, NITSs were 30–50 dB measured 24 h after the exposure; i.e., there is no evidence that an exposure resulting in < 40 dB TTS measured a few minutes after exposure can produce INJ. Therefore, an exposure producing 40 dB of TTS, measured a few minutes after exposure, can also be used as an upper limit to prevent INJ; i.e., it is assumed that exposures beyond those capable of causing 40 dB of TTS have the potential to result in INJ (which may or may not result in PTS).

1.4. ONSET TTS AND ONSET INJ

Navy thresholds for predicting auditory effects of sound on marine animals focus on defining thresholds for the onset of TTS and INJ (which includes, but is not limited to, PTS). In practice, it can be difficult to discern a "true" threshold elevation after noise exposure from typical variations in thresholds over time, therefore a TTS of 6 dB has been historically used to distinguish non-trivial amounts of TTS in marine mammals from fluctuations in threshold measurements that typically occur across test sessions (e.g., Ridgway et al., 1997; Schlundt et al., 2000; Southall et al., 2007; Southall et al., 2019). This is similar to the "standard threshold shift" concept applied to workplace hearing assessment (29 CFR 1910.95, 2008). Navy acoustic impact analyses therefore consider the onset of TTS to be 6 dB of TTS measured a few minutes (typ. 2–5 min) after exposure. Navy analyses assume that exposures resulting in a NITS ≥ 40 dB measured a few minutes after exposure may result in some amount of INJ and/or residual PTS. A TTS of 40 dB is therefore used as a proxy for the onset of INJ.

Sound levels just-capable of resulting in TTS or INJ are referred to as "onset" levels; e.g., an exposure just-capable of producing TTS is referred to as the onset-TTS exposure. Onset levels are treated as step functions or "all-or-nothing" thresholds: exposures above the TTS or INJ onset level are assumed to always result in TTS or INJ, while exposures below the TTS or INJ onset level are assumed to not cause TTS or INJ.

1.5. AUDITORY WEIGHTING FUNCTIONS

Animals are not equally sensitive to noise at all frequencies. To capture the frequency-dependent nature of the effects of noise, US Navy acoustic impact analyses use *auditory weighting functions*. Auditory weighting functions are mathematical functions used to emphasize frequencies where animals are more susceptible to noise exposure and de-emphasize frequencies where animals are less susceptible. The functions may be thought of as frequency-dependent filters that are applied to a noise exposure before a single, weighted sound level is calculated. The filters are normally "band-pass" in nature; i.e., the function amplitude resembles an inverted "U" when plotted versus frequency. The weighting function amplitude is approximately flat within a limited range of frequencies, called the "pass-band," and declines at frequencies below and above the pass-band.

1.6. PHASE 4 WEIGHTING FUNCTIONS AND TTS/INJ THRESHOLDS

Weighting function derivation for Navy Phase 3 was consistent with the National Marine Fisheries Service Technical Guidance (National Marine Fisheries Service, 2016; Department of the Navy, 2017; National Marine Fisheries Service, 2018). Marine mammal species were divided into groups for analysis. For each group, a frequency-dependent weighting function and numeric thresholds for the onset of TTS and INJ were derived from available data describing hearing abilities and effects of noise on marine mammal hearing. Measured or predicted auditory threshold data, as well as measured equal latency contours, were used to influence the weighting function shape for each group. For species groups for which TTS data were available, the weighting function parameters were adjusted to provide the best fit to the experimental data. Extrapolation methods were then used to derive parameters for the groups for which TTS data did not exist.

Since the derivation of Phase 3 acoustic criteria and thresholds, new data have been obtained regarding marine mammal hearing and the effects of noise on marine mammal hearing (e.g., see Tougaard et al., 2022). As a result, new weighting functions and TTS/INJ thresholds have been developed for Phase 4. Derivation of the new criteria and thresholds followed the same general approach utilized in Phase 3; however, some changes were made to accommodate new data, simplify the methodology, and align methods with recommendations from Southall et al. (2019).

1.7. USE OF MEAN/MEDIAN

At various steps during weighting function derivation, the central tendency of a dataset is needed. Since the underlying data are often limited, it can be difficult to identify whether the mean (average) value or median (50th percentile) value is the most appropriate estimate for the central tendency. Therefore, by convention, Phase 4 analyses utilize the mean value, unless there is evidence that the distribution of the underlying data is skewed (i.e., not normally distributed) or outliers exist. In these situations, the use of the median is specifically noted.

2. WEIGHTING FUNCTIONS AND EXPOSURE FUNCTIONS

As in Phase 3, the Phase 4 auditory weighting function shapes are based on a generic band-pass filter defined by the equation

$$W(f) = C + 10\log_{10}\left\{\frac{(f/f_1)^{2a}}{\left[1+(f/f_1)^2\right]^a\left[1+(f/f_2)^2\right]^b}\right\}, \tag{1}$$

where $W(f)$ is the weighting function amplitude (in dB) at the frequency f (in kHz). During implementation, the weighting function defined by Eq. (1) is used in conjunction with weighted thresholds for TTS and INJ for non-impulsive and impulsive exposures, expressed in units of sound exposure level (SEL).

For developing and visualizing the effects of the various weighting functions, it is helpful to invert Eq. (1), yielding

$$E(f) = K - 10\log_{10}\left\{\frac{(f/f_1)^{2a}}{\left[1+(f/f_1)^2\right]^a\left[1+(f/f_2)^2\right]^b}\right\}, \tag{2}$$

where $E(f)$ is the acoustic exposure level as a function of frequency f, the parameters f_1, f_2, a, and b are identical to those in Eq. (1), and K is a constant. The function described by Eq. (2) has a "U-shape" similar to an audiogram or equal loudness/latency contour (Figs. 1 and 2, right panels). K is defined to set the minimum value of $E(f)$ to match the weighted threshold for the onset of TTS or INJ, for non-impulsive or impulsive exposures. Equation (2) therefore describes how the exposure level necessary to cause TTS or INJ varies with frequency. The function defined by Eq. (2) is therefore referred to as an *exposure function*, since the curve defines the acoustic exposure that equates to onset TTS or INJ as a function of frequency. There are four exposure functions (and thus four separate values for K) for each species group: non-impulsive exposure TTS and INJ, and impulsive exposure TTS and INJ.

The shapes of the weighting function [Eq. (1)] and exposure function [Eq. (2)] are defined by the parameters C, K, f_1, f_2, a, and b (Figs. A.1 and A.2):

- C — *weighting function gain* (dB). The value of C defines the vertical position of the weighting function. Changing the value of C shifts the function up/down. The value of C is often chosen to set the maximum amplitude of W to 0 dB (i.e., the value of C does not necessarily equal the peak amplitude of the curve).

- K — *exposure function gain* (dB). The value of K defines the vertical position of the exposure function. Changing the value of K shifts the function up/down. The value of K is chosen to set the minimum amplitude of E to match the weighted threshold value. For each species group, separate values of K will exist for TTS (K_{TTS}) and injury (K_{INJ}) for non-impulsive and impulsive sounds.

- f_1 — *low-frequency cutoff* (kHz). The value of f_1 defines the lower limit of the filter pass-band; i.e., the lower frequency at which the weighting function amplitude begins to decline or "roll-off" from the flat, central portion of the curve. The specific amplitude at f_1 depends on the value of a. Decreasing f_1 will enlarge the pass-band of the function (the flat, central portion of the curve).

- f_2 — *high-frequency cutoff* (kHz). The value of f_2 defines the upper limit of the filter pass-band; i.e., the upper frequency at which the weighting function amplitude begins to roll-off from the flat, central portion of the curve. The amplitude at f_2 depends on the value of b. Increasing f_2 will enlarge the pass-band of the function.

a *low-frequency exponent* (dimensionless). The value of a defines the rate at which the weighting function amplitude declines with frequency at the lower frequencies. As frequency decreases, the change in weighting function amplitude becomes linear with the logarithm of frequency, with a slope of 20a dB/decade. Larger values of a result in lower weighting function amplitudes at f_1 and steeper roll-offs at frequencies below f_1.

b *high-frequency exponent* (dimensionless). The value of b defines the rate at which the weighting function amplitude declines with frequency at the upper frequencies. As frequency increases, the change in weighting function amplitude becomes linear with the logarithm of frequency, with a slope of -20b dB/decade. Larger values of b result in lower weighting function amplitudes at f_2 and steeper roll-offs at frequencies above f_2.

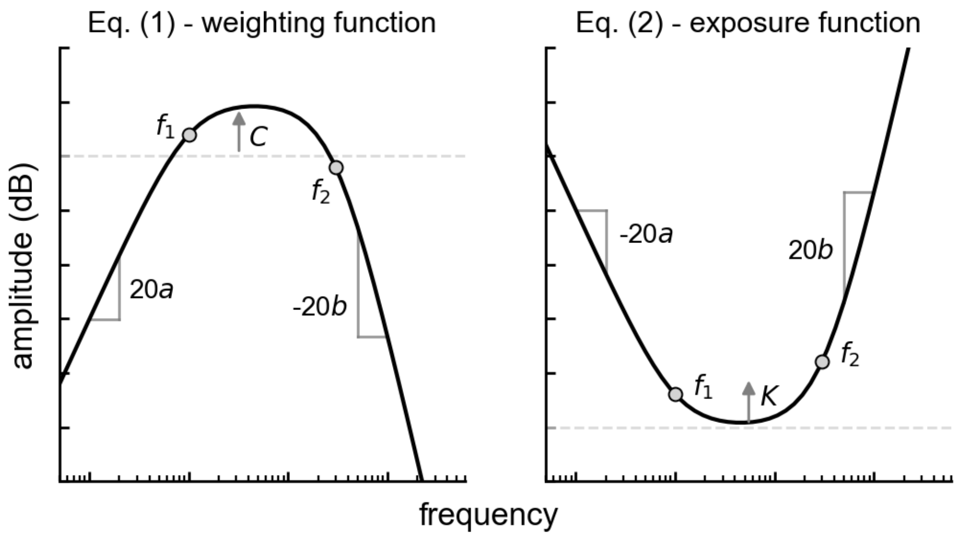

Figure A.1. Examples of (left) weighting function amplitude described by Eq. (1) and (right) exposure function amplitude described by Eq. (2). The parameters f_1 and f_2 specify the extent of the filter pass-band, while the exponents *a* and *b* control the rate of amplitude change below f_1 and above f_2, respectively. As the frequency decreases below f_1 or above f_2, the amplitude approaches linear-log behavior with a slope magnitude of 20*a* or 20*b* dB/decade, respectively. The constants *C* and *K* determine the vertical positions of the curves.

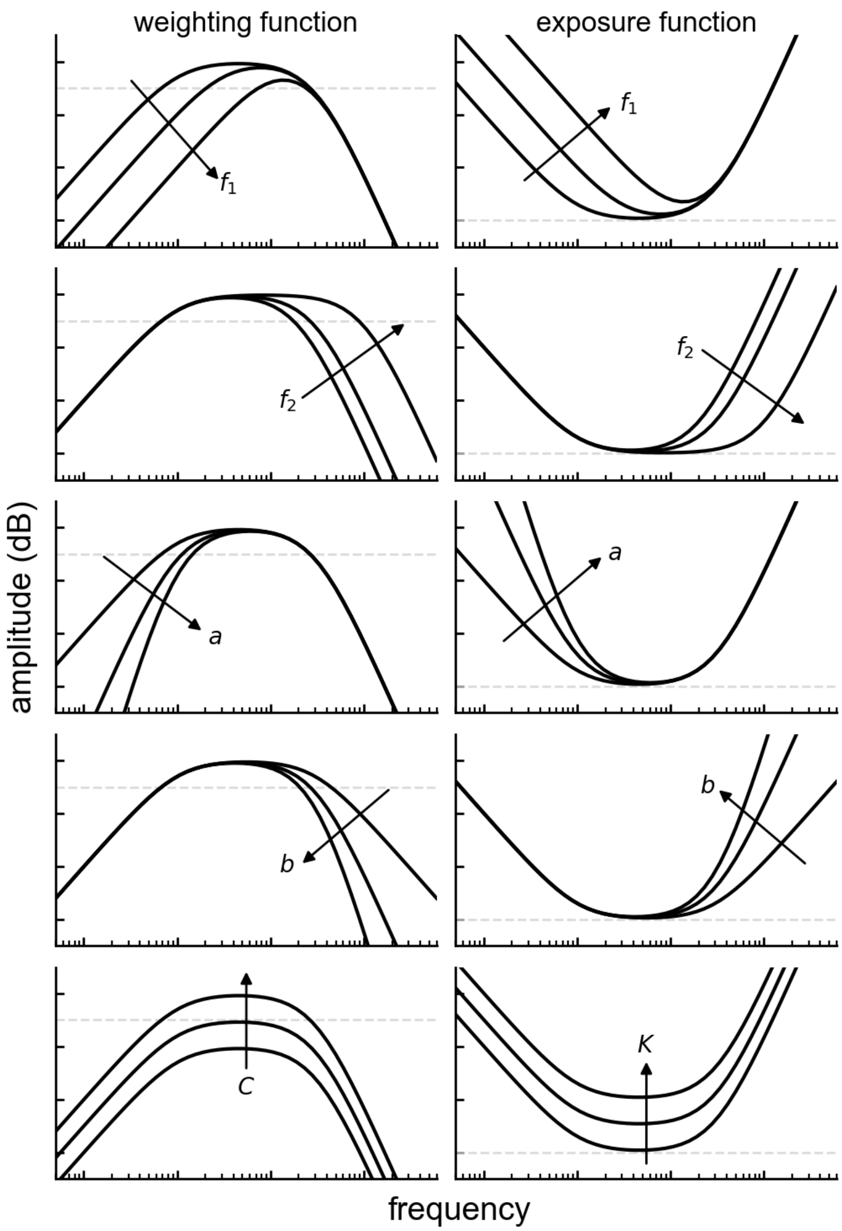

Figure A.2. Influence of parameter values on the resulting shapes of the weighting functions (left) and exposure functions (right). The arrows indicate the direction of change when the designated parameter is increased.

3. METHODOLOGY TO DERIVE FUNCTION PARAMETERS

Weighting and exposure functions are defined by selecting appropriate values for the parameters C, K, f_1, f_2, a, and b in Eqs. (1) and (2). Ideally, parameters for each group would be selected as those values resulting in the "best-fit" of Eq. (2) to experimental data describing the onset of TTS/INJ over a range of exposure frequencies, species, and individual subjects within that group. Data for the frequency-dependency of TTS in marine mammals exist, however they are limited at present, and there are no data showing frequency dependency of INJ in marine mammals. Therefore, in addition to TTS data, weighting and exposure function derivations also utilized auditory threshold measurements (audiograms), equal latency contours, and anatomical predictions of sensitivity.

For Phase 4, marine mammal species were divided into eight groups based on auditory, ecological, and phylogenetic relationships among species and the medium (air or water) in which they could be exposed. For each group, exposure/weighting functions and weighted thresholds were derived for impulsive and non-impulsive exposures. For the species groups containing sufficient data, TTS exposure functions were directly fit to the TTS data. The relationships between the exposure functions and audiogram shapes for these groups were then used as a basis for extrapolation to the other groups. This extrapolation relied on an assumption that TTS exposure functions would resemble the audiogram, but would show less change with frequency compared to audiograms.

Table A.1 lists the specific steps for function parameter derivation in Phase 4 and compares them to the steps used in Phase 3.

Table A.1. Steps used to define weighting function and exposure function parameters in Eqs. (1) and (2) for Phase 3 and Phase 4.

<table>
<tr><th>Step</th><th>Phase 3</th><th>Phase 4</th></tr>
<tr><td>1</td><td colspan="2">Marine mammal species were divided into groups.</td></tr>
<tr><td>2</td><td colspan="2">For each group, a representative, composite audiogram was estimated.</td></tr>
<tr><td>3</td><td colspan="2">The exponent a was defined as the smaller of the low frequency slope from the audiogram and equal latency contour.</td></tr>
<tr><td>4</td><td>The exponent b was set equal to two.</td><td>The exponent b was set equal to five.</td></tr>
<tr><td>5</td><td>f_1 and f_2 were defined as the frequencies where composite audiogram thresholds were ΔT-dB above the lowest threshold.
For groups with sufficient onset TTS data, the optimum value of ΔT was found by adjusting ΔT to best-fit Eq. (2) to the non-impulsive TTS onset data. This value of ΔT was used for the remaining groups.
The parameter K was then adjusted to fit Eq. (2) to available or estimated TTS onset data.</td><td>For groups with sufficient onset TTS data (delphinids, porpoises, otariids in water, and phocids in water), the parameters f_1, f_2, and K were adjusted to fit Eq. (2) to the non-impulsive TTS onset data. If the resulting exposure function bandwidth, defined as 10 dB above the minimum TTS onset value, did not meet or exceed that of the composite audiogram, f_1 was decreased and/or f_2 increased as necessary to ensure that the 10-dB bandwidth criterion was met.
For the remaining groups, f_1 and f_2 were defined so the differences between the audiogram thresholds at f_1 and f_2 and the minimum threshold (ΔT_1 and ΔT_2, respectively) matched the median value of ΔT_1 and mean value of ΔT_2 for the delphinids, porpoises, otariids in water, and phocids in water in water. The parameter K was then adjusted to fit Eq. (2) to available or estimated TTS onset data.</td></tr>
<tr><td>6</td><td colspan="2">The non-impulsive, weighted TTS threshold was defined as the minimum of the TTS exposure function.</td></tr>
<tr><td>7</td><td colspan="2">The parameter C was defined to set the peak amplitude of the weighting function to zero.</td></tr>
<tr><td>8</td><td colspan="2">The non-impulsive, weighted INJ threshold was found by adding a constant value (20 dB) to the weighted TTS thresholds.</td></tr>
<tr><td>9</td><td colspan="2">For groups with impulse TTS onset data, weighted SEL and peak SPL TTS thresholds for explosives and other impulsive sources were obtained from the available impulse TTS data. Weighted SEL and peak SPL INJ thresholds were estimated from the onset TTS thresholds. For other groups, the weighted SEL thresholds were estimated using the relationship between the steady-state TTS weighted threshold and the impulse TTS weighted threshold for the groups with data. Peak SPL thresholds were estimated using the relationship between hearing thresholds and the impulse TTS peak SPL thresholds for the groups with data.</td></tr>
</table>

4. MARINE MAMMAL SPECIES GROUPS

Marine mammals were divided into eight groups (Table A.2), with the same weighting function and TTS/INJ thresholds used for all species within a group. Species were grouped by considering their known or suspected audible frequency range, auditory sensitivity, ear anatomy, and acoustic ecology (i.e., how they use sound), as has been done previously (e.g., Ketten, 2000; Southall et al., 2007; Finneran and Jenkins, 2012; National Marine Fisheries Service, 2018; Southall et al., 2019).

4.1. Low-frequency cetaceans (group LF)

The LF cetacean group contains the mysticetes (baleen whales). Although there have been no direct measurements of hearing sensitivity in any mysticete, an audible frequency range of approximately 10 Hz to 30 kHz has been estimated from measured vocalization frequencies, observed reactions to playback of sounds, and anatomical analyses of the auditory system. A natural division may exist within the mysticete whales, with some species (e.g., blue, fin) having better low-frequency sensitivity and others (e.g., humpback, minke) having better sensitivity to higher frequencies; however, at present there is insufficient knowledge to justify separating species into multiple groups. Therefore, a single species group is used for all mysticetes.

4.2. High frequency cetaceans (group HF)

The HF cetacean group contains most delphinid species (e.g., bottlenose dolphin, common dolphin, killer whale, pilot whale), monodonts (belugas, narwhals), beaked whales, and sperm whales (but not pygmy and dwarf sperm whales of the genus *Kogia*, which are treated as very high frequency species). Hearing sensitivity has been directly measured for several species within this group using psychophysical (behavioral) or auditory evoked potential (AEP) measurements.

4.3. Very high frequency cetaceans (group VHF)

The VHF cetacean group contains the porpoises, river dolphins, pygmy/dwarf sperm whales, *Cephalorhynchus* species, and some *Lagenorhynchus* species. Hearing sensitivity has been measured for several species within this group using behavioral or AEP measurements. VHF cetaceans generally possess a higher upper-frequency limit and better sensitivity at higher frequencies compared to the HF cetacean species.

4.4. Sirenians (group SI)

The sirenian group contains manatees and dugongs. Behavioral and AEP threshold measurements for manatees have revealed lower upper-cutoff frequencies and lower sensitivities (higher thresholds) compared to the HF cetaceans.

4.5. Phocid carnivores (groups PCA, PCW)

This group contains all earless seals or “true seals,” including all Arctic and Antarctic ice seals, harbor or common seals, gray seals and inland seals, elephant seals, and monk seals. Since these animals are amphibious, weighting functions and TTS/INJ thresholds are included for both airborne (group PCA) and underwater exposure (group PCW). Aerial and underwater hearing thresholds exist for some Northern Hemisphere species in this group. There is emerging evidence suggesting that a natural division may exist within the family Phocidae, with species within the subfamily Monachinae having lower hearing sensitivity and less susceptibility to noise compared to the subfamily Phocinae (Kastak et al., 2005; Sills et al., 2021); however, data exist from only single individuals from two Monachid species and there is insufficient knowledge to justify separation into two groups at this time.

4.6. Otariids and other non-phocid marine carnivores (groups OCA, OCW)

This group contains all eared seals (fur seals and sea lions), walruses (Odobenidae), sea otters (Mustelidae), and polar bears (Ursidae). The division of marine carnivores by placing phocids in one group and all others into a second group was made after considering auditory anatomy and measured audiograms for the various species and noting the similarities between the non-phocid audiograms (see Fig. A.1-1, Appendix A.1). Aerial and underwater hearing thresholds exist for some Northern Hemisphere species in this group. Separate weighting functions and TTS/INJ thresholds are included for airborne (group OCA) and underwater exposure (group OCW).

Table A.2. Marine mammal species group designations for Navy Phase 4 auditory weighting functions.

Code	Name	Members
LF	Low frequency cetaceans	Balaenidae (right and bowhead whales): *Eubalaena* spp., *Balaena* Balaenopteridae (rorquals): *Balaenoptera* spp., *Megaptera* Eschrichtiidae (gray whale): *Eschrichtius* Neobalenidae (pygmy right whale): *Caperea*
HF	High frequency cetaceans	Physeteridae (sperm whale): *Physeter* Ziphiidae (beaked whales): *Berardius* spp., *Hyperoodon* spp., *Indopacetus*, *Mesoplodon* spp., *Tasmacetus*, *Ziphius* Delphinidae (killer whale, melon-headed whale, false/pygmy killer whale, pilot whales, some dolphin species): *Orcinus*, *Delphinus*, *Feresa*, *Globicephala* spp., *Grampus*, *Lagenodelphis*, *Lagenorhynchus acutus*, *L. albirostris*, *L. obliquidens*, *L. obscurus, Lissodelphis* spp., *Orcaella* spp., *Peponocephala*, *Pseudorca*, *Sotalia* spp., *Sousa* spp., *Stenella* spp., *Steno*, *Tursiops* spp.
VHF	Very high frequency cetaceans	Delphinidae (some dolphin species): *Cephalorhynchus* spp.; *Lagenorhynchus cruciger*, *L. australis* Phocoenidae (porpoises): *Neophocaena* spp., *Phocoena* spp., *Phocoenoides* Iniidae (Amazon river dolphin): *Inia* Kogiidae(Pygmy/dwarf sperm whale): *Kogia* Lipotidae (Baiji): *Lipotes* Pontoporiidae (La Plata dolphin): *Pontoporia*
SI	Sirenians	Trichechidae (manatees): *Trichechus* spp. Dugongidae (dugongs): *Dugong*
OCW OCA	Otariids and other non-phocid marine carnivores (water) Otariids and other non-phocid marine carnivores (air)	Odobenidae (walrus): *Odobenus* Otariidae (fur seals and sea lions): *Arctocephalus* spp., *Callorhinus*, *Eumetopias*, *Neophoca*, *Otaria*, *Phocarctos*, *Zalophus* spp. Mustelidae (sea/marine otter): *Enhydra*, *Lontra feline* Ursidae (polar bear): *Ursus maritimus*
PCW PCA	Phocids (water) Phocids (air)	Phocidae (true seals): *Cystophora*, *Erignathus*, *Halichoerus*, *Histriophoca*, *Hydrurga*, *Leptonychotes*, *Lobodon*, *Mirounga* spp., *Monachus*, *Neomonachus*, *Ommatophoca*, *Pagophilus*, *Phoca* spp., *Pusa* spp.

5. COMPOSITE AUDIOGRAMS

Composite audiograms for each species group were determined by first searching the available literature for threshold data for the species of interest. For each group, all available AEP and psychophysical (behavioral) threshold data were initially examined. To derive the composite audiograms, the following rules were applied:

1. For all marine mammal groups except LF cetaceans, only behavioral (i.e., no AEP) data were used. Mammalian AEP thresholds are typically elevated from behavioral thresholds in a frequency-dependent manner, with increasing discrepancy between AEP and behavioral thresholds at the lower frequencies where there is a loss of phase synchrony in the neurological responses and a concomitant increase in measured AEP thresholds. The frequency-dependent relationship between the AEP and behavioral data is problematic for defining the audiogram slope at low frequencies, since the AEP data will systematically over-estimate thresholds and therefore over-estimate the low-frequency slope of the audiogram.

   For LF cetaceans, for which no behavioral or AEP threshold data exist, hearing thresholds were estimated by synthesizing predictions from anatomical measurements and mathematical models of hearing, and animal vocalization frequencies (see Appendix A.2).

2. Data from an individual animal were included only once at a particular frequency. If data from the same individual were available from multiple studies, typically the earlier published data were used, when the individual was younger and less likely to exhibit age-related hearing loss. In some cases, data judged to be more representative or of higher quality were used, or data at overlapping frequencies were averaged. These cases are noted in Tables A.1-1 and A.1-2 (Appendix A.1).

3. Individuals with obvious high-frequency hearing loss for their species or aberrant audiograms (e.g., obvious notches or thresholds known to be elevated for that species due to auditory masking or hearing loss) were excluded.

Table A.1-1 (Appendix A.1) lists the individual audiogram data ultimately used to construct the composite audiograms (for all species groups except the LF cetaceans). Table A.1-2 lists the data that were excluded, along with the rationale for exclusion.

In contrast to Phase 3, where composite audiograms were derived using the original (absolute) threshold values and normalized threshold values, composite audiograms are only derived in Phase 4 using the actual threshold data (not normalized). Normalized audiograms are excluded in Phase 4 to simplify the analysis and to avoid inherent problems in normalizing datasets that do not contain the frequency region of best sensitivity.

Combining individual datasets requires a common set of frequency values. Therefore, frequency values for each individual were replaced with frequencies spaced at 1/12-octave intervals, encompassing the range of frequencies present in the original data. Threshold values at the 1/12-octave frequencies were obtained by linear-log interpolation (linear thresholds, logarithmic frequencies) between sequential data points. Figure A.3 shows an example of the interpolation process.

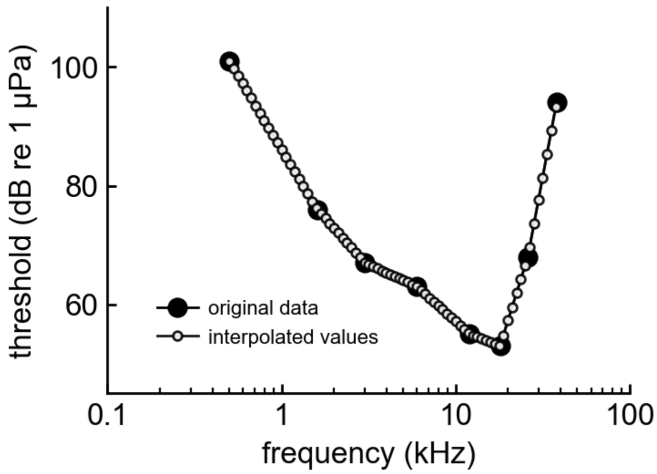

Figure A.3. **To ensure common frequencies across studies, threshold data for each study were interpolated onto a grid of frequencies, logarithmically spaced at 1/12-octave intervals.**

From these data, the median threshold value was calculated at each frequency and fit by the function

$$T(f) = T_0 + A \log_{10}\left(1 + \frac{F_1}{f}\right) + \left(\frac{f}{F_2}\right)^B, \tag{3}$$

where $T(f)$ is the threshold at frequency f, and T_0, F_1, F_2, A, and B are fitting parameters. The median value was used to reduce the influence of outliers. The particular form of Eq. (3) was chosen to provide linear-log roll-off with variable slope at low frequencies and a steep rise at high frequencies. Equation (3) was fit to the median threshold data using the *curve_fit* function in the optimize module of the python package SciPy (Virtanen et al., 2020).

For Phase 4, composite audiograms were derived using the median value of the individual threshold data (as in Phase 3). From a statistical perspective, it would be better to first compute the median threshold for each species, then compute the overall median value for each group from the species' medians. This would prevent a species from being over-represented in the final median value. In practice, however, this approach is more sensitive to the quality of individual audiograms, especially when the number of species is small. This is illustrated in Figure A.1-2, which compares composite audiograms derived using the two methods.

The resulting fitting parameters and goodness of fit values (R^2) are provided in Table 3. Because of the large number and possible high dependency of fitting parameters, in some cases the specific fitting parameter values may not make physical sense (e.g., HF group F_1 = 9910 kHz); the important point is how well the resulting curve fits the median threshold data. Equation (3) was also used to describe the shape of the estimated audiogram for the LF cetaceans, with the parameter values chosen to provide reasonable thresholds based on the limited available data regarding mysticete hearing (see Appendix A.2 for details).

Figure A.4 shows the threshold data and composite audiograms based on the fitted curve for each species group. The composite audiograms for each species group are compared to each other in Fig. 5, and to the Phase 3 audiograms in Fig. A.6.

From the composite audiograms, the frequency of lowest threshold, F_0, and the slope at the lower frequencies (over a 3-octave span), were calculated (Tables A.3 and A.4).

Table A.3. Composite audiogram parameter values for use in Eq. (3). For all groups except LF cetaceans, values represent the best-fit parameters from fitting Eq. (3) to median values derived from experimental threshold data. For the LF cetaceans, parameter values for Eq. (3) were estimated as described in Appendix B. The parameter F_0 is the frequency corresponding to the minimum threshold (Min Thresh). Min Thresh has units of dB re 1 µPa for underwater groups and dB re 20 µPa for in-air groups (OCA and PCA only).

Group	T_0 (dB)	F_1 (kHz)	F_2 (kHz)	A	B	R^2	F_0 (kHz)	Min Thresh (dB SPL)
LF	54.2	0.412	3.73	20.0	1.79	—	2.82	56
HF	-38.9	9910	10.5	33.5	1.66	0.979	38.5	51
VHF	48.2	4.95	132	46.8	24.5	0.994	117	49
OCW	9.90	74.0	0.170	33.3	0.786	0.938	6.17	64
PCW	55.1	0.391	8.56	48.4	1.79	0.954	6.67	57
SI	-13.7	1680	7.87	33.1	2.52	0.996	15.6	59
OCA	6.90	1.04	8.86	63.7	2.78	0.990	9.00	11
PCA	-36.2	2.38	0.0188	52.6	0.581	0.976	2.73	-3.8

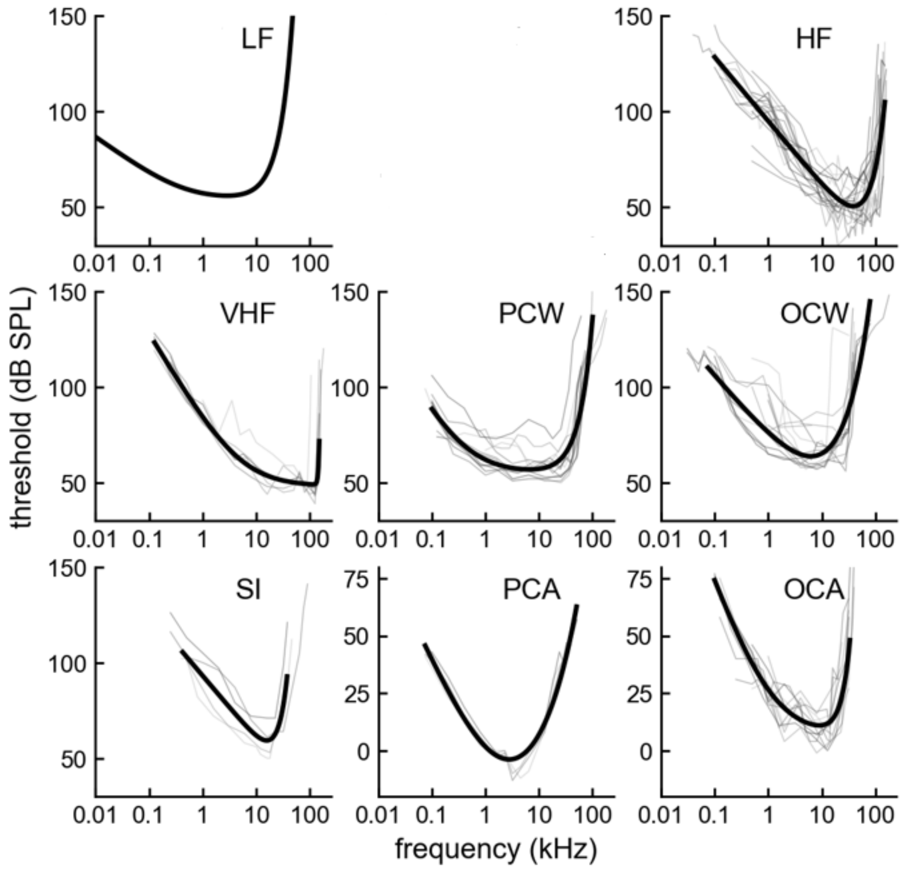

Figure A.4. **Thresholds and composite audiograms for the marine mammal species groups. Thin lines represent the threshold data from individual animals. Thick lines represent the Phase 4 composite audiograms. Thresholds are expressed in dB re 1 µPa for underwater data and dB re 20 µPa for in-air data (groups OCA and PCA only). Appendix A.1 lists the individual audiograms used to derive the composite functions. Derivation of the LF cetacean curve is described in Appendix A.2.**

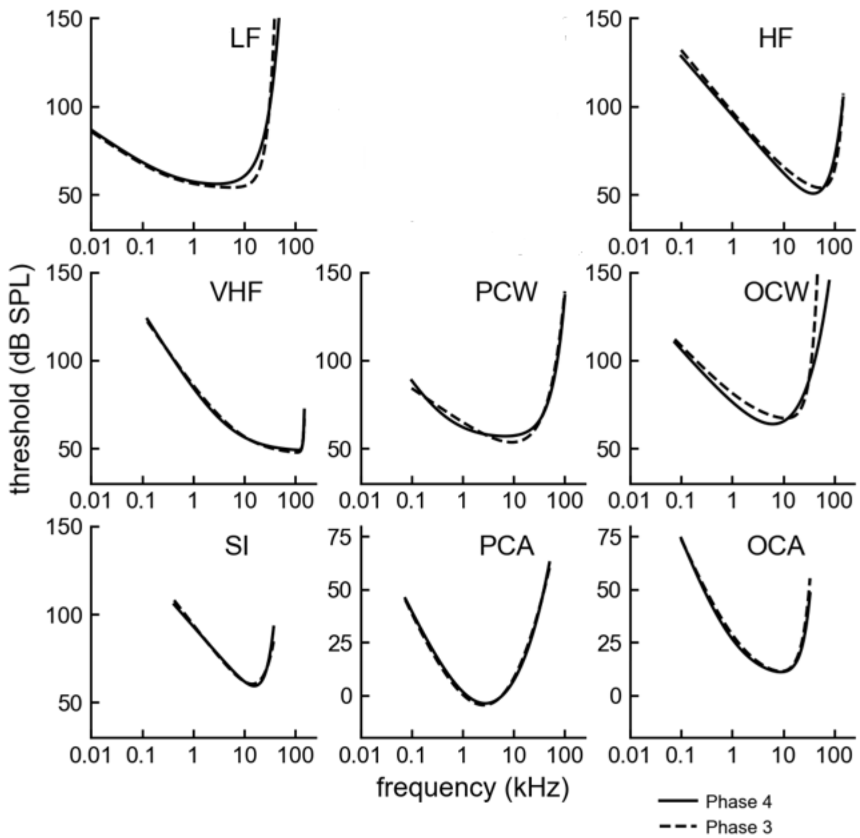

Figure A.5. **Comparison of Phase 3 and Phase 4 composite audiograms. Thresholds are expressed in dB re 1 μPa for underwater data and dB re 20 μPa for in-air data (groups OCA and PCA only).**

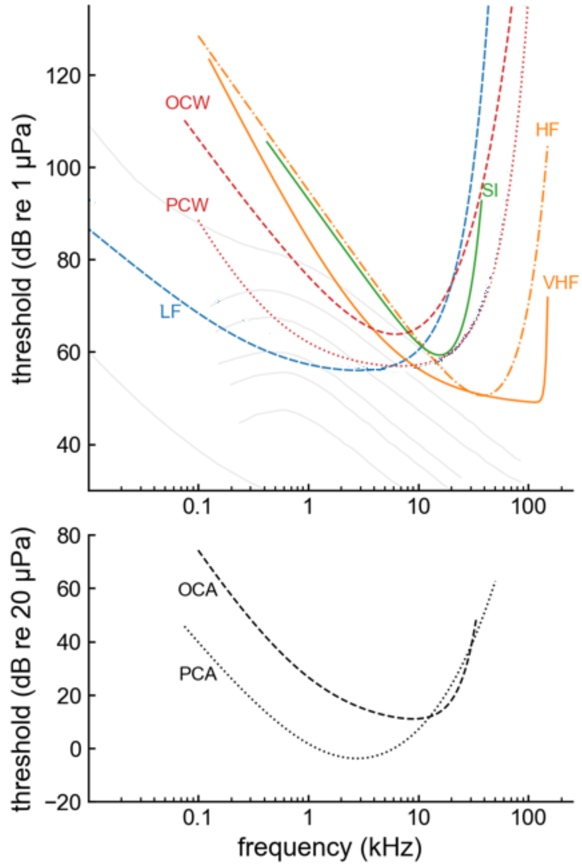

Figure A.6. **Composite audiograms for the various species groups underwater (upper) and in-air (lower). The thin (gray) lines in the upper panel represent ambient noise spectral density levels (referenced to the left ordinate, but in dB re 1 µPa^2/Hz) corresponding to the limits of prevailing noise (upper and lower traces) and various sea-state conditions, from 0.5 to 6 (National Research Council (NRC), 2003).**

Table A.4. Frequency of best hearing (F_0) and the magnitude of the low-frequency slope derived from composite audiograms (Aud. slope) and equal latency contours (Eq. lat. slope). Audiogram slopes were calculated across a frequency range of 3 octaves beginning with the lowest frequency present for each group. Equal latency slopes were calculated from the available equal latency contour data (Reichmuth, 2013; Wensveen et al., 2014; Mulsow et al., 2015).

Group	F_0 (kHz)	Aud. slope (dB/dec)	Eq. lat. slope (dB/dec)
LF	2.82	20	—
HF	38.5	34	31
VHF	117	45	50
OCW	6.17	32	—
PCW	6.67	33	—
SI	15.6	33	—
OCA	9.00	55	27
PCA	2.73	45	41

6. TTS DATA REVIEW

6.1. NON-IMPULSIVE (STEADY-STATE) EXPOSURES – TTS ONSET

Figure A.7 shows the non-impulsive TTS data available for each marine mammal group. The symbol style indicates the amount of TTS produced by that combination of exposure frequency and SEL: open symbols, TTS < 6 dB; filled symbols, TTS ≥ 6 dB; transparency indicates the relative amount of TTS (less transparent means larger TTS).

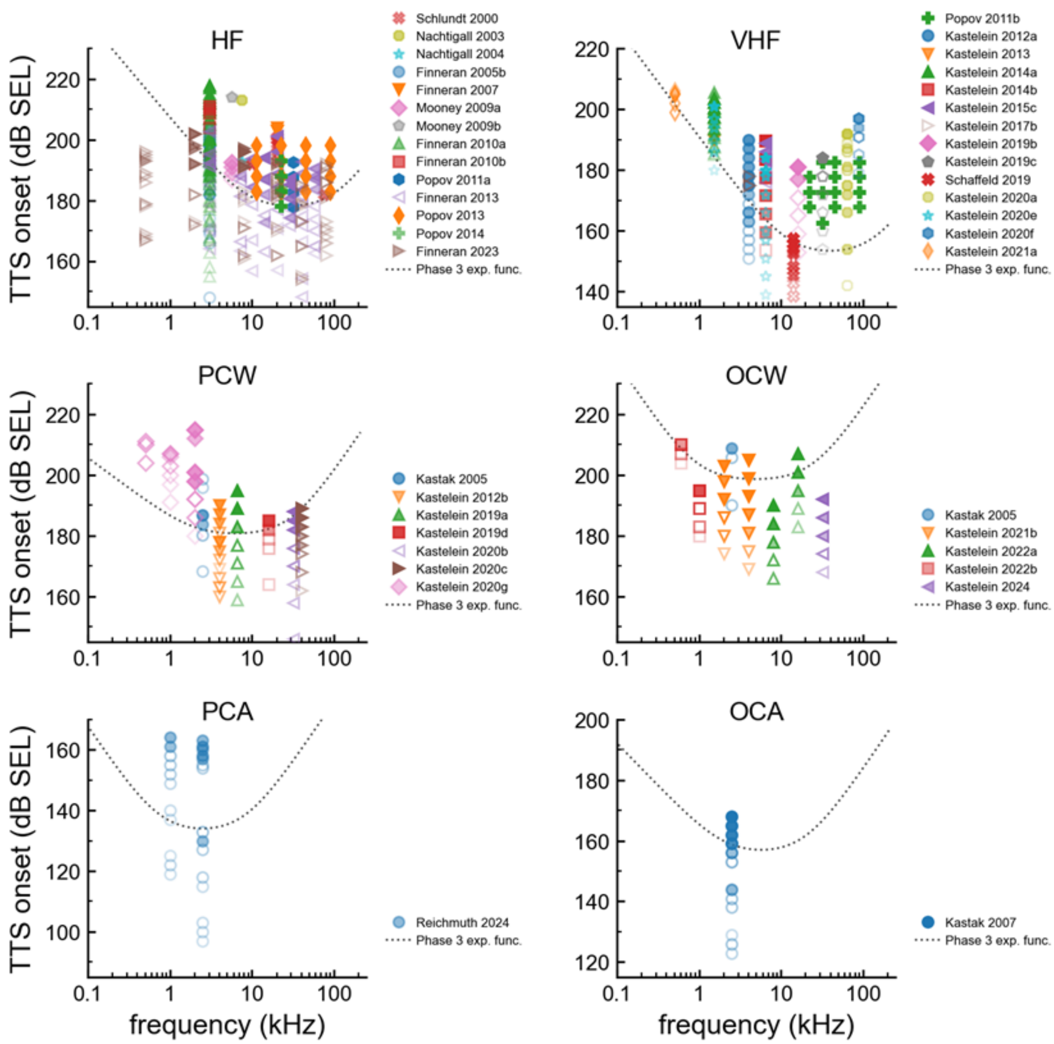

Figure A.7. Summary of available TTS data for each marine mammal group. Open symbols indicate combinations of exposure frequency and SEL that resulted in < 6 dB of mean TTS. Filled symbols indicate combinations of exposure frequency and SEL that resulted in ≥ 6 dB of mean TTS. The transparency of each symbol indicates the relative amount of TTS; i.e., less transparent symbols indicate more TTS. Units for TTS onset are dB re 1 μPa^{2}s in water (groups HF, VHF, PCW, OCW) and re (20 μPa)^{2}s in air (groups OCA, PCA).

For weighting/exposure function derivation, the most critical data are TTS onset exposure levels as a function of exposure frequency — for species groups with sufficient data, the parameters in Eq. (2) are adjusted so the exposure function matches these TTS onset data. TTS onset values are estimated from published literature by examining TTS as a function of SEL for various frequencies. As in Phase 3, only TTS data from psychophysical (behavioral) hearing tests were used (National Marine Fisheries Service, 2016; Department of the Navy, 2017; National Marine Fisheries Service, 2018; Southall et al., 2019).

To determine TTS onset for each subject, the amount of TTS observed after exposures with different SPLs and durations (Figure 7) were combined to create a single TTS growth curve as a function of SEL. The use of (cumulative) SEL is a simplifying assumption to accommodate sounds of various SPLs, durations, and duty cycles. This is referred to as an “equal energy” approach, since SEL is related to the energy of the sound and this approach assumes exposures with equal SEL result in equal effects, regardless of the duration or duty cycle of the sound. It is well-known that the equal energy rule may over-estimate the effects of intermittent noise, since the quiet periods between noise exposures will allow some recovery of hearing compared to noise that is continuously present with the same total SEL (Ward, 1997). For continuous exposures with the same SEL but different durations, the exposure with the longer duration has often produced more TTS (e.g., Kastak et al., 2007; Mooney et al., 2009b; Finneran et al., 2010b). Despite these limitations, the equal energy rule is still a useful concept because it includes the effects of both noise amplitude and duration when predicting auditory effects. SEL is a simple metric, allows the effects of multiple noise sources to be combined in a meaningful way, has physical significance, and is correlated with most TTS growth data reasonably well — in some cases even across relatively large ranges of exposure duration (see Finneran, 2015). Marine mammal TTS studies have shown that TTS generally increases with SEL in an accelerating fashion: At low exposure SELs, the amount of TTS is small and the growth curves have shallow slopes. At higher SELs, the growth curves generally become steeper and approach linear relationships with the noise SEL. Accordingly, most TTS growth data were fit with the function

$$t(L) = m_1 \log_{10}\left[1 + 10^{(L-m_2)/10}\right], \tag{4}$$

where t is the amount of TTS, L is the SEL, and m_1 and m_2 are fitting parameters. This particular function has an increasing slope when $L < m_2$ and approaches a linear relationship for $L > m_2$ (Maslen, 1981). The linear portion of the curve has a slope of $m_1/10$ and an x-intercept of m_2. Fitting was accomplished using the *curve_fit* function in the optimize module of the python package SciPy (Virtanen et al., 2020).

Some TTS data do not fit the accelerating growth predicted by Eq. (4), but instead show some amount of growth followed by a plateau, where further increases in SEL do not result in increasing TTS (referred to as asymptotic threshold shift). These datasets were visually identified and fit instead with the function

$$t(L) = \frac{T_F}{1 + 10^{p(L_0 - L)}}, \tag{5}$$

where t is the amount of TTS, L is the SEL, and T_F, p, and L_0 are fitting parameters. This function has a value of zero when $L << L_0$, then increases and asymptotically approaches T_F when $L >> L_0$. Fitting was done with the *curve_fit* function in the optimize module of the python package SciPy (Virtanen et al., 2020).

After fitting Eq. (4) or (5) to the TTS growth data, the SEL necessary to induce 6 dB of TTS was determined. Extrapolation was not performed when estimating TTS onset; this means only data sets with exposures producing TTS both above and below 6 dB were used to estimate TTS onset.

Figures A.3-1 to A.3-5 (Appendix A.3) show all behavioral TTS data to which growth curves defined by Eq. (4) or (5) could be fit. The TTS onset exposure values, growth rates, and references to these data are provided in Tables A.3-1 to A.3-5. The resulting TTS onset SELs as functions of frequency are summarized in Figure A.8, with the Phase 3 composite audiograms and exposure functions for comparison. Figure A.9 also shows additional data not used for TTS onset determination, either because the data were from AEP measurements, or all TTSs were > 6 dB (thus TTS onset could not be determined).

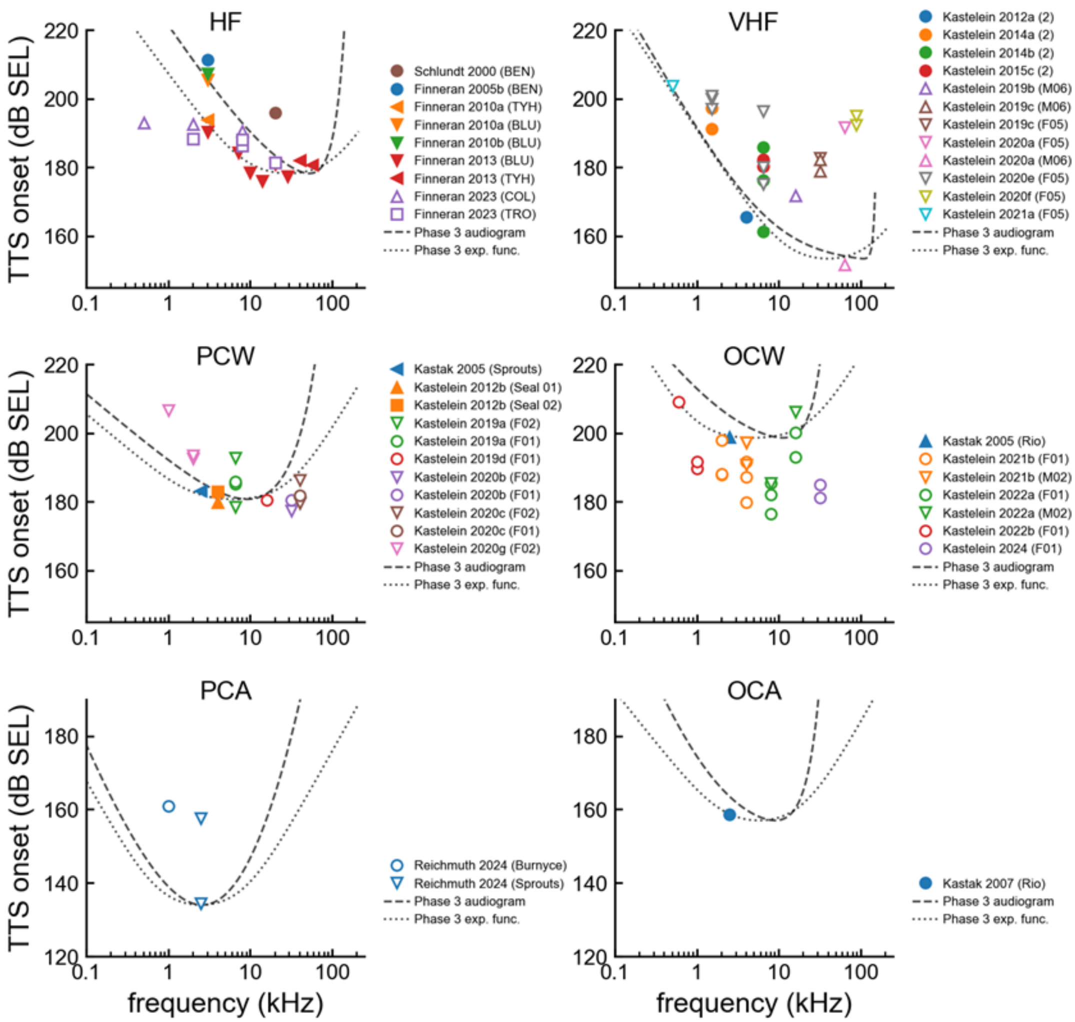

Figure A.8. SELs corresponding to TTS onset for each marine mammal species group, obtained from TTS growth functions (see Appendix C). Solid symbols indicate data that were available for Phase 3; open symbols indicate new data since Phase 3 analyses. Dashed line – Phase 3 composite audiogram. Dotted line – Phase 3 exposure function. Units for TTS onset are dB re 1 μPa²s in water (groups HF, VHF, PCW, OCW) and re (20 μPa)²s in air (groups OCA, PCA).

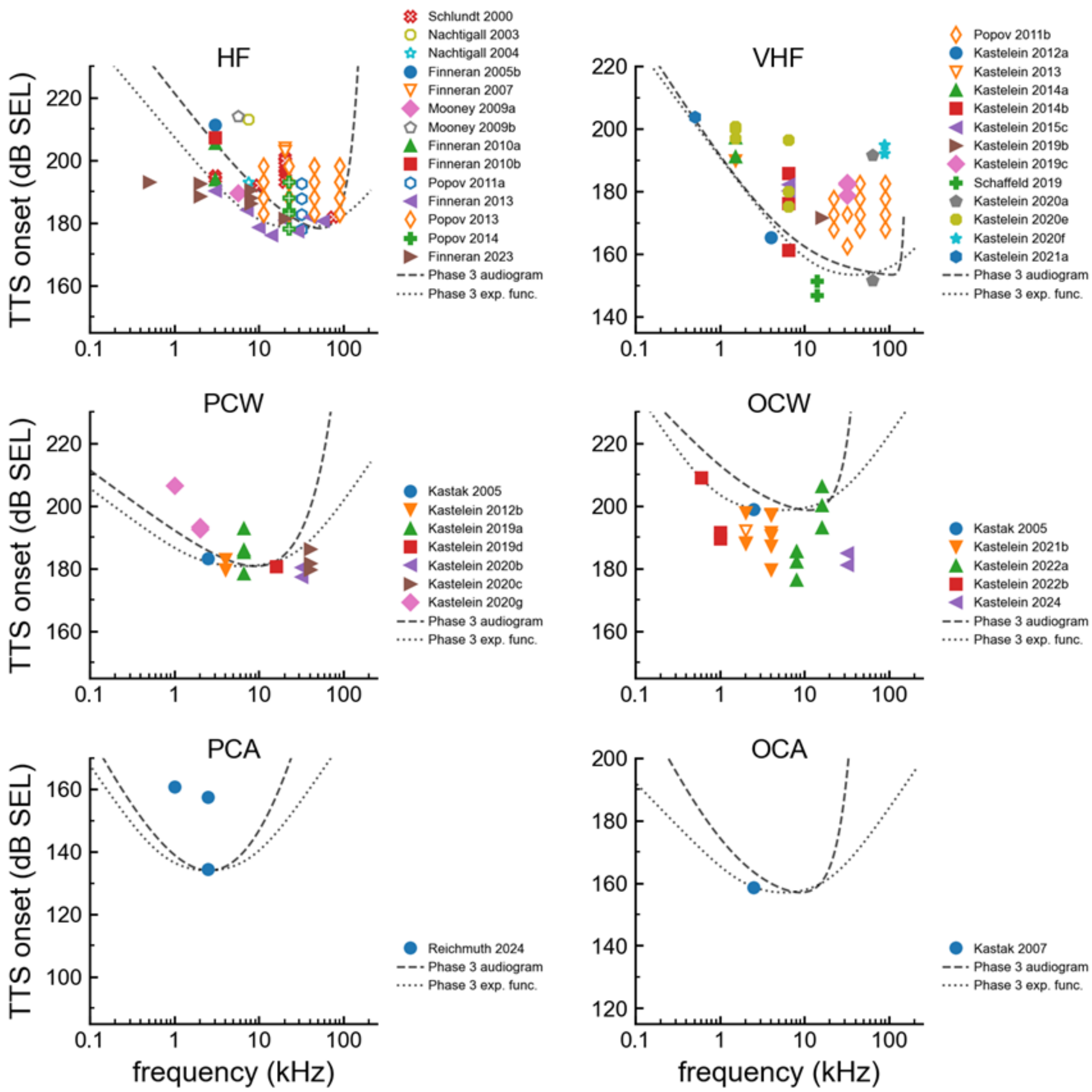

Figure A.9. **SELs corresponding to TTS ≥ 6 dB for each marine mammal species group. Solid symbols indicate onset TTS data obtained by interpolation within TTS growth functions (Appendix C); open symbols indicate data with TTS ≥ 6 dB, but for which TTS onset could not be determined. Dashed line – Phase 3 composite audiogram. Dotted line – Phase 3 exposure function. Units for TTS onset are dB re 1 μPa²s in water (groups HF, VHF, PCW, OCW) and dB re (20 μPa)²s in air (groups OCA, PCA).**

For fitting the exposure function parameters in Eq. (2), the data shown in Fig. 8 were reduced to a single value at each frequency for each group (otherwise, some frequencies would exert more influence on the fitting process than others). This was accomplished by first identifying multiple data for the same animal at a single exposure frequency. This typically occurred when hearing was tested at multiple frequencies after an exposure, or exposures with different duty cycles were utilized. In these cases, only the single, lowest onset-TTS exposure level was utilized (the others were excluded from further analysis). Similarly, TTS onset data obtained from post-exposure testing at extended time periods (e.g., >5 min post-exposure) were eliminated from further analysis. The mean SEL for TTS onset was then computed at each frequency for which more than one data point existed. Figure A.10 shows the resulting mean onset TTS SELs versus exposure frequency for each group.

Finally, some mean TTS onset data points for groups VHF and PCW (represented with an open circle in Fig. A.10) were excluded from the fitting process. This was done as a precautionary measure, where new data indicate higher TTS onset values than those predicted by Phase 3, but uncertainties in the data suggest that some caution should be exercised:

> For VHF, new data suggest substantially higher onset TTS SELs at frequencies above ~10 kHz compared to the Phase 3 predictions, with high variability in the TTS onset data for harbor porpoises at 63 kHz (~40 dB difference in TTS onset for the two porpoises). Furthermore, the harbor porpoise behavioral TTS onset SELs are significantly higher than SELs resulting in large amounts (e.g., 23–45 dB) of AEP TTS in Yangtze finless porpoise (see Fig. A.8). Although some differences in AEP/behavioral TTS data are expected, these large differences indicate that caution is warranted in adopting the high-frequency behavioral TTS data at the present time. For this reason, the VHF behavioral TTS onset data at frequencies > 10 kHz were not used during the exposure function fitting process.
>
> For PCW, new data below 2.5 kHz show significantly higher TTS onset compared to the Phase 3 predictions. It is surprising that the harbor seal TTS onset data at 1-2 kHz are ~10 dB higher than that of dolphins, given the better hearing sensitivity for seals at lower frequencies. The slope of the TTS data at low frequencies is also substantially higher than the audiogram slope (47 vs 33 dB/dec); this is also unexpected: the increased spread of excitation within the cochlea at the high sound levels associated with TTS would be expected to make the TTS slope shallower than the audiogram slope, not steeper. There are also uncertainties regarding the effective exposure level for the seals, since the animals spent a significant amount of time at the water's surface during the noise exposures, suggesting the animals may have behaviorally mitigated the exposure. Given these concerns and the limited nature of the data at present, harbor seal TTS onset data below 2.5 kHz were excluded from the Phase 4 fitting process.
>
> For PCA, substantially higher TTS onset was observed in the N. elephant seal compared to the harbor seal. These data fit emerging evidence suggesting that Monachinae have lower hearing sensitivity and less susceptibility to noise compared to Phocinae, and thus TTS onset for Monachinae would be too high for Phocinae. Therefore, the N. elephant seal data were excluded from the Phase 4 fitting process.

Note that even though these data are not directly used in the fitting process, they are still considered in evaluating the final exposure function (i.e., there is no question that TTS occurred, so the mean TTS onset SELs should be above the resulting exposure function). As additional data become available, the decision whether to include these data will be re-assessed. Future studies may increase confidence in these data and thus warrant their direct inclusion in the fitting process.

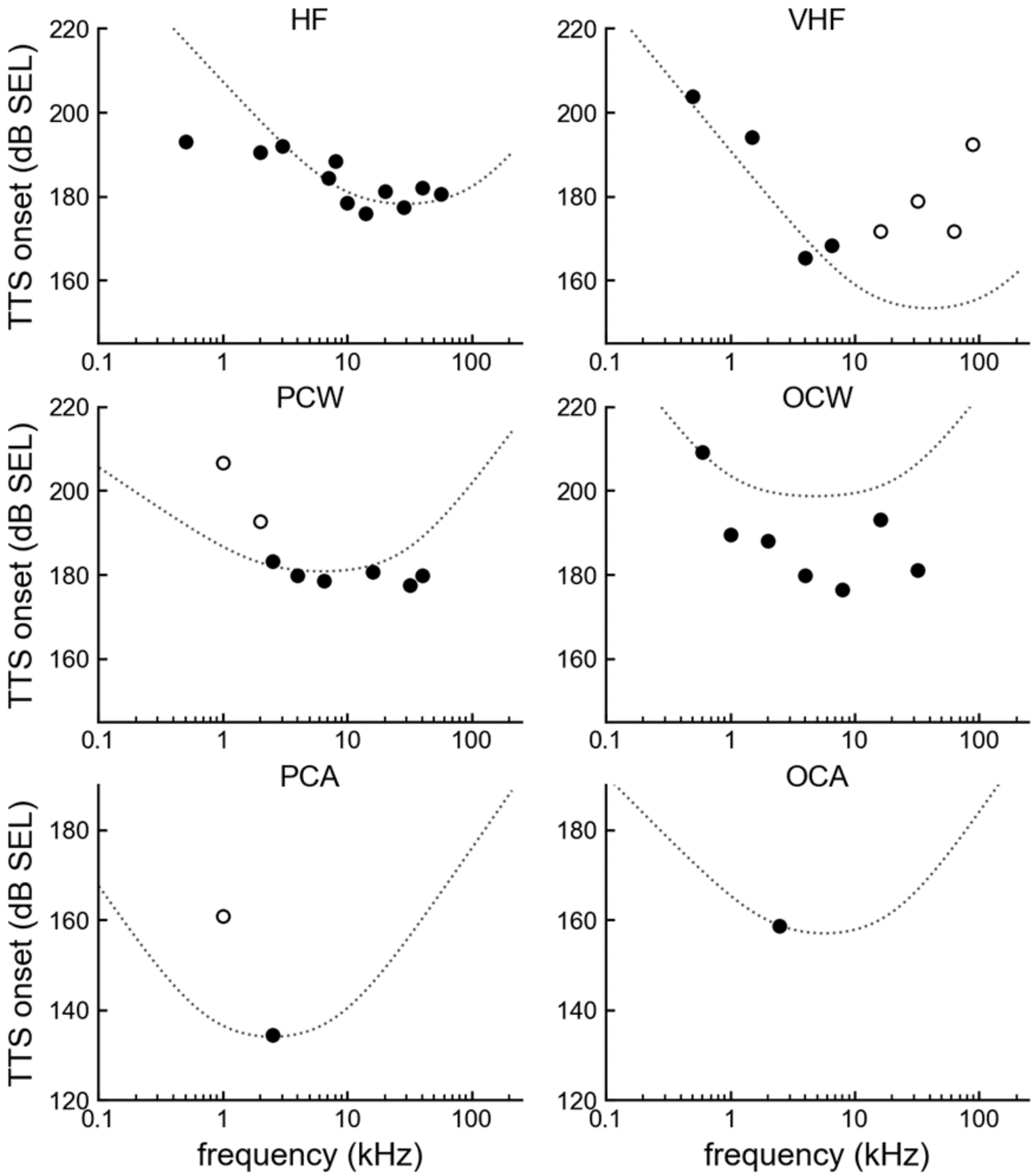

Figure A.10. Mean TTS onset SELs for each species group as a function of exposure frequency. Open symbols indicate mean onset TTS data that were not used during the fitting process. The dotted line shows the Phase 3 exposure function.

6.2. Non-impulsive (steady-state) exposures – INJ onset

There has been one documented occurrence of PTS in a marine mammal after an intense noise exposure: Reichmuth et al. (2019) reported a PTS of 8 dB at 5.8 kHz in a harbor seal after exposure to a 4.1 kHz tone with (unweighted) SEL of 199 dB re 1 μPa^{2}s. The initial TS (1 min post-exposure) was ~57 dB. Although these data are not suitable for directly deriving INJ thresholds, they provide an opportunity to compare the resulting INJ threshold value to actual PTS data.

Beyond Reichmuth et al. (2019), there are no direct data relating auditory injury to noise exposure in marine mammals, thus exposures producing 40 dB TTS were used as a proxy to estimate onset INJ. Since few marine mammal TTS studies have resulted in 40 dB of TTS, TTS growth curves were extrapolated to determine the SEL required for a TTS of 40 dB. To avoid over-estimating INJ onset by using growth curves based on small amounts of TTS, where the growth rates are shallower than at higher amounts of TTS, extrapolation was only performed if the measured TTS exceeded 20 dB. From these growth curves, the SEL difference between TTS onset (6-dB TTS) and estimated INJ onset (40-dB TTS) was calculated (see Figs. A.3-1 to A.3-5, Tables A.3-1 to A.3-5).

6.3. Impulsive exposures

Marine mammal TTS data from impulsive sources are limited to four studies with measured TTS of 6 dB or more (Table 5):

> Finneran et al. (2002) reported behaviorally measured TTSs of 6 and 7 dB in a beluga exposed to single impulses from a seismic water gun (unweighted SEL = 186 dB re 1 μPa^{2}s, peak SPL = 224 dB re 1 μPa).
>
> Lucke et al. (2009) reported AEP-measured TTS of 7 to 20 dB in a harbor porpoise exposed to single impulses from a seismic air gun (unweighted SEL 165–166 dB re 1 μPa^{2}s, peak SPL of 195 dB re 1 μPa). Note that the data from Lucke et al. (2009) are based on AEP measurements; however, they are used here because of the limited nature of the impulse TTS data for marine mammals and the likelihood that the VHF cetaceans are more susceptible than the HF cetaceans (i.e., use of the HF cetacean value is not appropriate). Based on the limited data, it is reasonable to assume that the exposures described by Lucke et al. (2009), which produced AEP-measured TTS of up to 20 dB, would have resulted in a behavioral TTS of at least 6 dB.
>
> Sills et al. (2020b) reported TTS of 6 dB in a bearded seal after exposure to four impulses from a seismic air gun (unweighted, single-impulse SEL of 185 dB re 1 μPa^{2}s or peak SPL of 203 dB re 1 μPa). Note that when the same individual was exposed to single impulses with the same peak SPL, no measurable mean TTS was obtained, therefore these data cannot be used to establish a peak SPL threshold.
>
> Mulsow et al. (2022) behaviorally measured TTS in three dolphins exposed to sequences of narrowband (1/6-octave), 10-ms noisebursts centered at 8 kHz (unweighted, single-impulse SEL ~160 dB re 1 μPa^{2}s or peak SPL ~183 dB re 1 μPa). Inter-pulse intervals ranged from 1.25 to 40 s and the number of impulses varied from 40 to 2560. Maximum mean TTS was 16 dB. At the same peak SPLs, some conditions (i.e., fewer impulses) produced no TTS, therefore these data cannot be used to establish a peak SPL threshold.

The small reported amounts of TTS and/or the limited distribution of exposures prevent these data from being used to estimate INJ onset.

Several impulsive noise exposure studies have also resulted in < 6 dB (behavioral) TTS (see Table A.5):

> HF: Finneran et al. (2000) exposed dolphins and belugas to single impulses from an "explosion simulator" (maximum unweighted SEL = 179 dB re 1 μPa^{2}s, peak SPL = 217 dB re 1 μPa) and Finneran et al. (2015) exposed three dolphins to sequences of 10 impulses from a seismic air gun (maximum unweighted cumulative SEL = 193 to 195 dB re 1 μPa^{2}s, peak SPL = 196 to 210 dB re 1 μPa) without measurable TTS.

VHF: Kastelein et al. (2015b) reported behaviorally measured mean TTS of 4 dB at 8 kHz and 2 dB at 4 kHz after a harbor porpoise was exposed to a series of impulsive sounds produced by broadcasting underwater recordings of impact pile driving strikes through underwater sound projectors (simulated impact pile driving). The exposure contained 2760 individual impulses presented at an interval of 1.3 s (total exposure time was 1 h). The average single-impulse, unweighted SEL was approximately 146 dB re 1 μPa^{2}s and the cumulative (unweighted) SEL was approximately 180 dB re 1 μPa^{2}s. Kastelein et al. (2016) observed behaviorally measured mean TTS up to 3 dB at 4 kHz and 5 dB at 8 kHz after harbor porpoises were exposed to up to 16560 simulated impact pile strikes. The average single-impulse, unweighted SEL was approximately 145 dB re 1 μPa^{2}s and the maximum cumulative (unweighted) SEL was approximately 187 dB re 1 μPa^{2}s. Kastelein et al. (2017c) measured mean TTS of 3–4 dB at 4 kHz after a harbor porpoise was exposed to 10–20 impulses from a pair of seismic air guns. The average single-impulse, unweighted SEL was approximately 178 dB re 1 μPa^{2}s, the maximum cumulative (unweighted) SEL was approximately 191 dB re 1 μPa^{2}s, and the maximum peak SPL was 199 dB re 1 μPa. Subsequent testing with four airguns and cumulative SELs up to 199 dB re 1 μPa^{2}s produced maximum mean TTS of 3 dB (Kastelein et al., 2020g).

OCW: Finneran et al. (2003) exposed two sea lions to single impulses from an arc-gap transducer with no measurable TTS (maximum unweighted SEL = 163 dB re 1 μPa^{2}s, peak SPL = 203 dB re 1 μPa).

PCW: Reichmuth et al. (2016) exposed two spotted seals (*Phoca largha*) and two ringed seals (*Pusa hispida*) to single impulses from a 10 in^3 sleeve air gun with no measurable TTS (maximum unweighted SEL = 181 dB re 1 μPa^{2}s, peak SPL ~ 203 dB re 1 μPa). Kastelein et al. (2018) exposed two harbor seals to simulated impact pile driving strikes with single-impulse, unweighted SEL ~151 dB re 1 μPa^{2}s, maximum cumulative (unweighted) SEL ~193 dB re 1 μPa^{2}s, and maximum peak SPL ~176 dB re 1 μPa. The maximum observed TTS was 4 dB.

Table A.5. Summary of existing data for marine mammal TTS from impulsive sources. SEL values are in dB re 1 μPa²s. Peak SPL values are in dB re 1 μPa. Exposures with cumulative SEL associated with onset TTS are indicated by an asterisk in the "TTS onset, SEL" column. For these exposures, $C_s – C_i$ is the difference between the onset TTS weighted SEL threshold for non-impulsive and impulsive exposures. Exposures with peak SPL associated with onset TTS are indicated by an asterisk in the "TTS onset, peak SPL" column. For these exposures, "peak SPL dynamic range" indicates the difference (in dB) between the peak SPL TTS onset (in dB re 1 μPa) and the hearing threshold at f_0 (in dB re 1 μPa).

Study	Group	Subject	Peak SPL (dB SPL)	Wgt. SEL (dB SEL)	Num. impulses	Cumulative wgt SEL (dB SEL)	TTS onset, SEL	C_s - C_i (dB SEL)	TTS onset, peak SPL	Peak SPL dynamic range (dB SPL)
Finneran 2000	HF	BEN, MUK	217	176	1	176		—		—
Finneran 2002	HF	MUK	224	177	1	177	*	4.0	*	173
Finneran 2015	HF	BLU, TYH, OLY	210	157	10	167		—		—
Mulsow 2023	HF	OLY	183	162	40	178	*	3.0		—
Mulsow 2023	HF	TRO	183	159	40	175	*	6.0		—
Mulsow 2023	HF	TYH	183	160	640	188	*	-7.0		—
Kastelein 2015b	VHF	2	180	112	2760	146		—		—
Kastelein 2016	VHF	02, 04	—	110	16560	152		—		—
Kastelein 2017c	VHF	6	199	136	20	149		—		—
Kastelein 2020d	VHF	6	202	—	40	—		—		—
Lucke 2009	VHF	Eigil	196	144	1	144	*	17	*	147
Finneran 2003	OCW	NRT, LIB	203	157	1	157		—		—
Kastelein 2018	PCW	01, 02	176	143	16560	185		—		—
Reichmuth 2016	PCW	TUNU, AMAK, NATCHEK, NAYAK	203	158	1	158		—		—
Sills 2020b	PCW	Noatak	203	162	4	168	*	7.0		—

7. TTS EXPOSURE FUNCTIONS FOR SONARS

7.1. OVERVIEW

Derivation of the parameters for the weighting/exposure functions consisted of two main steps: First, for groups with sufficient TTS onset data, the parameters K, a, b, f_1, and f_2 were determined. Then, extrapolation procedures were used to derive the exposure function shapes for the remaining groups. The specific steps are described in the following sections.

7.2. LOW- AND HIGH-FREQUENCY EXPONENTS (*A*, *B*)

As in Phase 3, the low-frequency exponent, a, was defined as $a = s_0/20$, where s_0 is the lower of the slope of the audiogram or equal latency curves (in dB/decade) at low frequencies (Table 4). This causes the weighting function slope to match the shallower slope of the audiogram or equal latency contours at low frequencies. This approach was used instead of directly using the low-frequency slope of the TTS onset data because of the limited number of data points available for TTS onset at low frequencies compared to the audiogram data (e.g., VHF, PCW, OCW) and/or weak fits to the data (e.g., HF).

The high-frequency exponent, b, was fixed at $b = 5$, which is higher than that used in the Phase 3 functions (b=2). The value was increased to better fit the OCW function without substantially affecting the other group fits.

7.3. FREQUENCY CUTOFFS (F_1, F_2) AND GAIN PARAMETER (K)

For groups HF, VHF, OCW, and PCW, nonlinear regression was used to find values of K, f_1, and f_2 to best-fit Eq. (2) to the onset TTS data. Nonlinear regression was performed using the *curve_fit* function in the optimize module of the python package SciPy (Virtanen et al., 2020). For some datasets, Eq. (2) can exhibit high dependency among the parameters, resulting in small changes in the function despite large changes in parameter values. This can cause problems in extrapolating to the other groups. Therefore, the optimization process was constrained so that $f_L \leq f_1 \leq F_0$ and $F_0 \leq f_2 \leq f_H$, where f_L and f_H are the frequencies below and above F_0 (the composite audiogram frequency of best hearing), respectively, where the composite audiogram thresholds were 40 dB above the minimum audiogram threshold at F_0.

Following each curve-fit, the frequencies at which the resulting exposure function amplitude exceeded the minimum value by 10 dB were compared to the corresponding frequencies for the composite audiogram (see Figure 11). If the lower exposure function frequency was above the audiogram frequency, the parameter f_1 was adjusted downward until the exposure function and audiogram frequencies matched. Similarly, if the upper exposure function frequency was below the audiogram frequency, the parameter f_2 was adjusted upward until the exposure function and audiogram frequencies matched. This procedure ensured that the exposure function 10-dB bandwidth was at least as wide as the audiogram, since it is expected that the high sound levels capable of causing TTS would cause the exposure function to “flatten” relative to the audiogram. The practical effect of this step was to decrease f_1 for the PCW and OCW groups and increase f_2 for the VHF group.

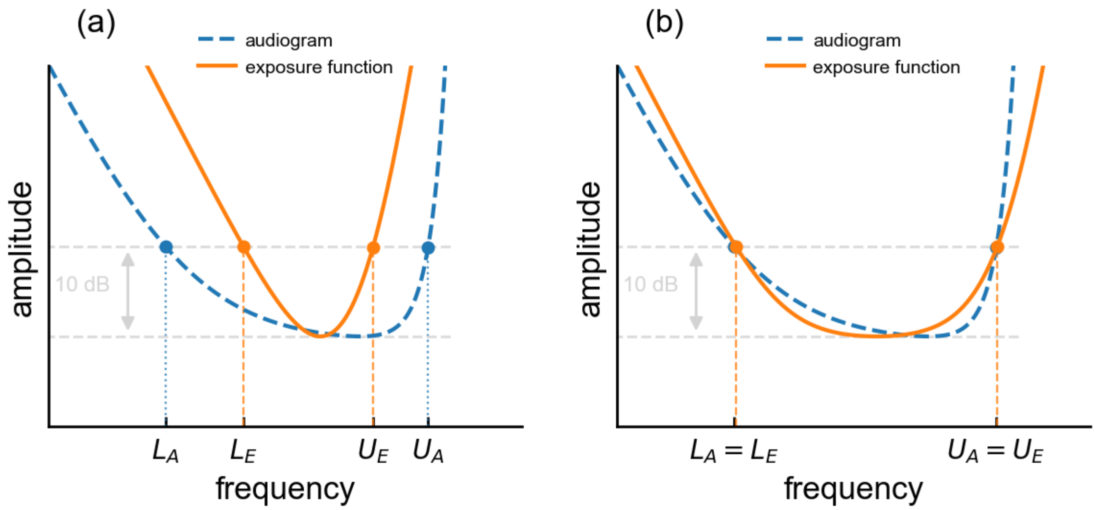

Figure A.11. **(a) After fitting Eq. (2) to the onset TTS data, the frequencies at which the exposure function amplitude was 10 dB above the minimum (L_E and U_E) were compared to the corresponding frequencies in the composite audiogram (L_A and U_A, respectively). (b) If $L_E > L_A$, then f_1 in Eq. (2) was iteratively decreased until $L_E = L_A$. Similarly, if $U_E < U_A$, f_2 in Eq. (2) was iteratively increased until $U_E = U_A$.**

To determine f_1 and f_2 for the remaining groups, the parameters ΔT_1 and ΔT_2 were defined, such that ΔT_1 was the amount that the composite audiogram threshold at f_1 exceeded the minimum threshold value, and ΔT_2 was the amount that the composite audiogram threshold at f_2 exceeded the minimum threshold value. After determining the best-fit values of f_1, f_2, and K for groups HF, VHF, OCW, and PCW, ΔT_1 and ΔT_2 were determined for each group: ΔT_1 = 36.8, 11.5, 3.9, 6.5 dB and ΔT_2 = 38.6, 22.7, 38.9, 39.4 dB, for HF, VHF, OCW, and PCW, respectively. For ΔT_1, the value at 36.8 appears to be an outlier; therefore the median value of ΔT_1 (9.0 dB) and the mean of ΔT_2 (34.9 dB) were used in conjunction with the composite audiograms for the LF, SI, PCA, and OCA groups to determine f_1 and f_2.

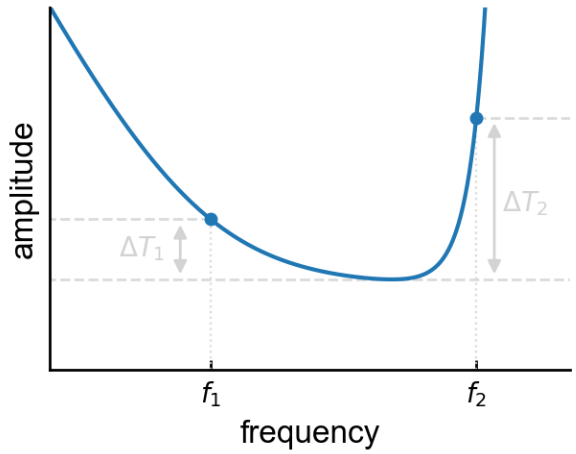

Figure A.12. The parameter ΔT_1 was defined as the amount that the composite audiogram threshold at f_1 exceeded the minimum threshold value. Similarly, ΔT_2 was defined as the amount that the composite audiogram threshold at f_2 exceeded the minimum threshold value. Central tendencies of ΔT_1 and ΔT_2 were computed for the groups HF, VHF, OCW, and PCW. For the remaining groups, f_1 and f_2 were defined as the lower and upper frequencies where the composite audiogram was ΔT_1 and ΔT_2 dB above the minimum value.

For the groups with TTS data (PCA, OCA), the gain parameter *K* was defined to minimize the mean squared error between the exposure function and TTS data for each species group.

For the low-frequency cetaceans and sirenians, for which no TTS data exist, TTS onset at the frequency of best hearing (F_0) was estimated by assuming the numeric difference between the auditory threshold (in dB SPL) at F_0 and the onset of TTS (in dB SEL) at F_0 would be similar to that for the in-water marine mammal groups. Table 6 summarizes the onset TTS and composite threshold data for the HF, VHF, OCW, and PCW groups. For these groups, the mean difference between TTS onset and composite audiogram threshold at F_0 was 121 dB. For the LF group, the hearing threshold at F_0 is 56 dB re 1 μPa, therefore the TTS onset value at F_0 is 177 dB re 1 μPa^{2}s (Table A.5). For the SI group, the lowest threshold was 59 dB re 1 μPa, making the onset TTS estimate 180 dB re 1 μPa^{2}s (Table 6). The value of *K* was then defined so the TTS exposure function matched the estimated TTS onset at F_0.

Table A.6. Differences between composite audiogram threshold values (Fig. A.4) and TTS onset values at the frequency of best hearing (F_0). The values for the low-frequency cetaceans and sirenians were estimated using the mean difference (121) from the HF, VHF, OCW, and PCW groups.

Group	F_0 (kHz)	Threshold at F_0 (dB SPL)	TTS onset at F_0 (dB SEL)	Difference	Estimated difference	Estimated TTS onset at F_0 (dB SEL)
LF	2.82	56	—	—	121	177
HF	38.5	51	183	132	—	—
VHF	117	49	167	118	—	—
OCW	6.17	64	180	116	—	—
PCW	6.67	57	176	118	—	—
SI	15.6	59	—	—	121	180
OCA	9.00	11	158	147	—	—
PCA	2.73	-3.8	134	138	—	—

Once *K* was determined, the weighted threshold for onset TTS was determined from the minimum value of the exposure function. Finally, the constant *C* was determined by substituting parameters *a*, *b*, f_1, and f_2 into Eq. (1) and adjusting *C* so the maximum amplitude of the weighting function was 0 dB.

Table A.7 summarizes the various function parameters, the weighted TTS thresholds, and the goodness of fit values between the TTS exposure functions and the mean onset TTS data. Figures A.13–A.17 show the exposure functions for each group.

Table A.7. Weighting function and non-impulsive TTS/INJ exposure function parameters for use in Eqs. (1) and (2) for non-impulsive (steady-state) exposures. R^2 values represent goodness of fit between the exposure function and the mean TTS onset data (Appendix A.3, Fig. A.13 filled symbols).

Group	a	b	f_1 (kHz)	f_2 (kHz)	C (dB)	K_{TTS} (dB)	Weighted TTS threshold (dB SEL)	K_{INJ} (dB)	Weighted INJ threshold (dB SEL)	R^2
LF	0.990	5.00	0.168	26.6	0.120	177	177	197	197	—
HF	1.55	5.00	1.73	129	0.320	181	181	201	201	0.247
VHF	2.23	5.00	5.93	186	0.910	160	161	180	181	0.903
OCW	1.58	5.00	2.53	43.8	1.37	178	179	198	199	0.541
PCW	1.63	5.00	0.810	68.3	0.290	175	175	195	195	-4.69
SI	1.66	5.00	5.91	37.6	3.61	176	180	196	200	—
OCA	1.35	5.00	1.75	32.5	1.18	156	157	176	177	—
PCA	2.05	5.00	0.739	24.4	0.830	133	134	153	154	—

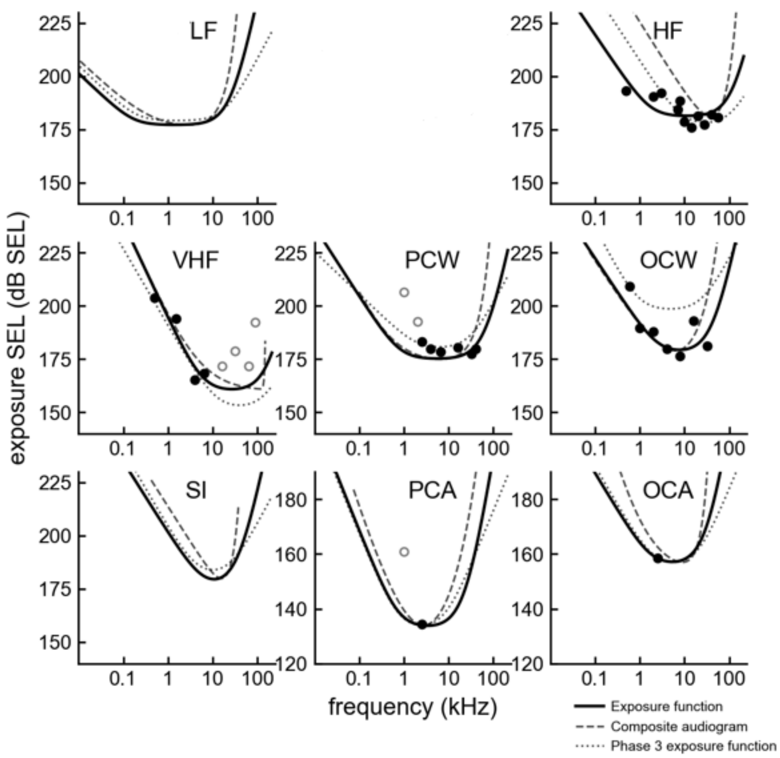

Figure A.13. TTS Exposure functions (solid lines) for non-impulsive exposures, generated from Eq. (2) with the parameters specified in Table A.7. Dashed lines — (normalized) composite audiograms. Audiograms were normalized (for display only) by adding a constant value to equate the minimum audiogram value with the exposure function minimum. Dotted lines — Navy Phase 3 exposure functions for TTS onset for each group. Filled symbols — mean onset TTS exposure data (in dB SEL) used to define exposure function shape and vertical position. Open symbols — mean onset TTS data not used to fit exposure functions.

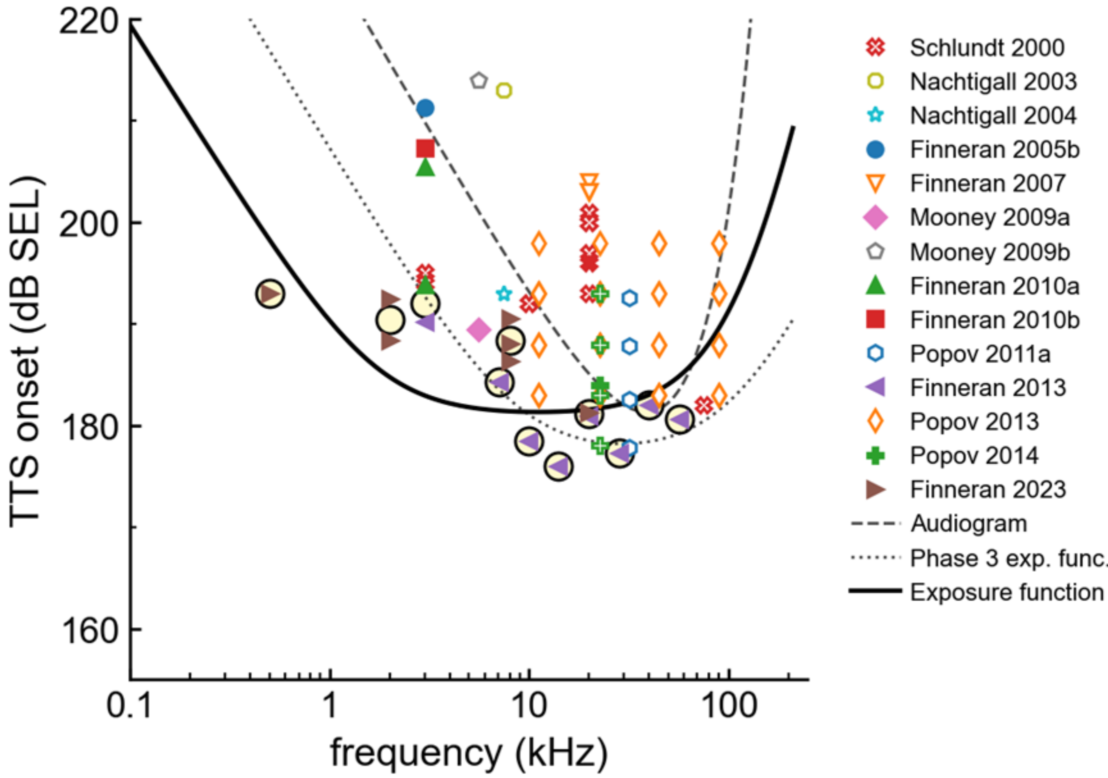

Figure A.14. **HF cetacean non-impulsive exposure function, (normalized for display only) composite audiogram, and Phase 3 exposure function compared to HF cetacean TTS data ≥ 6 dB. Filled symbols — onset TTS data (Appendix A.3). Open symbols — SELs producing TTS ≥ 6 dB for which TTS onset could not be determined. Large, yellow-filled circles indicate (mean) TTS onset values used during the fitting process.**

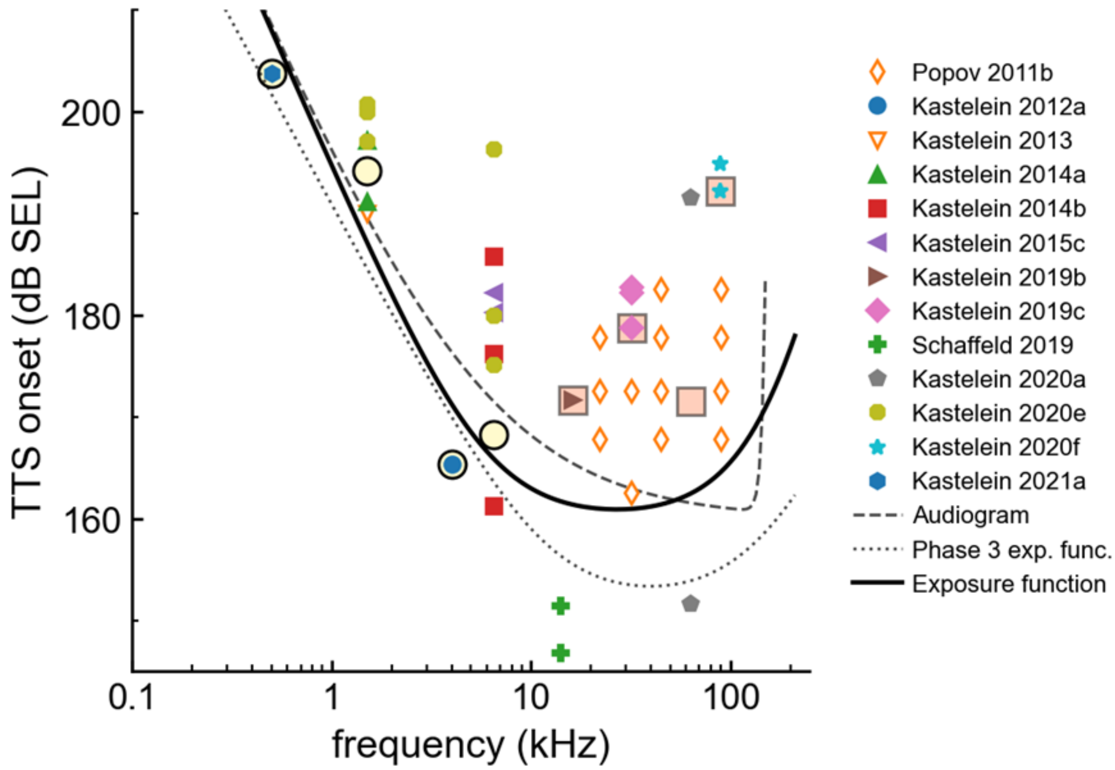

Figure A.15. VHF cetacean non-impulsive exposure function, (normalized for display only) composite audiogram, and Phase 3 exposure function compared to VHF cetacean TTS data ≥ 6 dB. Filled symbols — onset TTS data (Appendix A.3). Open symbols — SELs producing TTS ≥ 6 dB for which TTS onset could not be determined. Large, yellow-filled circles indicate (mean) TTS onset values used during the fitting process. Large, red-filled squares indicate (mean) TTS onset values excluded from the fitting process.

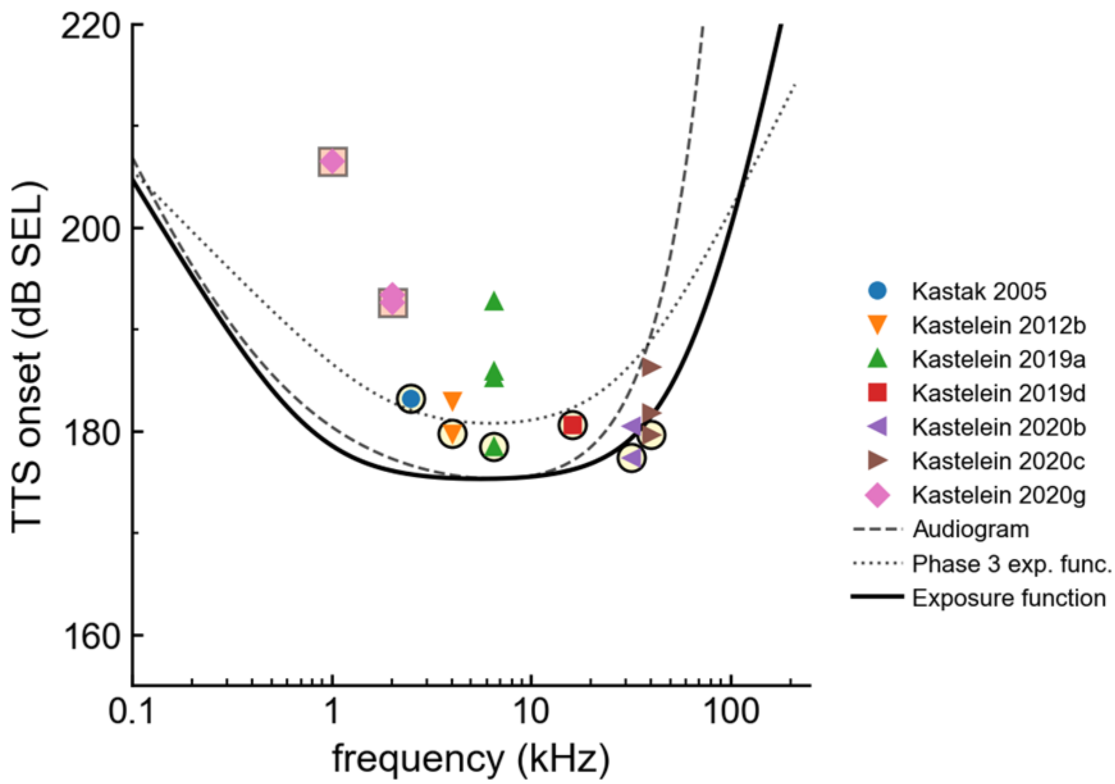

Figure A.16. PCW non-impulsive exposure function, (normalized for display only) composite audiogram, and Phase 3 exposure function compared to PCW TTS data ≥ 6 dB. Filled symbols — onset TTS data (Appendix A.3). Large, yellow-filled circles indicate (mean) TTS onset values used during the fitting process. Large, red-filled squares indicate (mean) TTS onset values excluded from the fitting process.

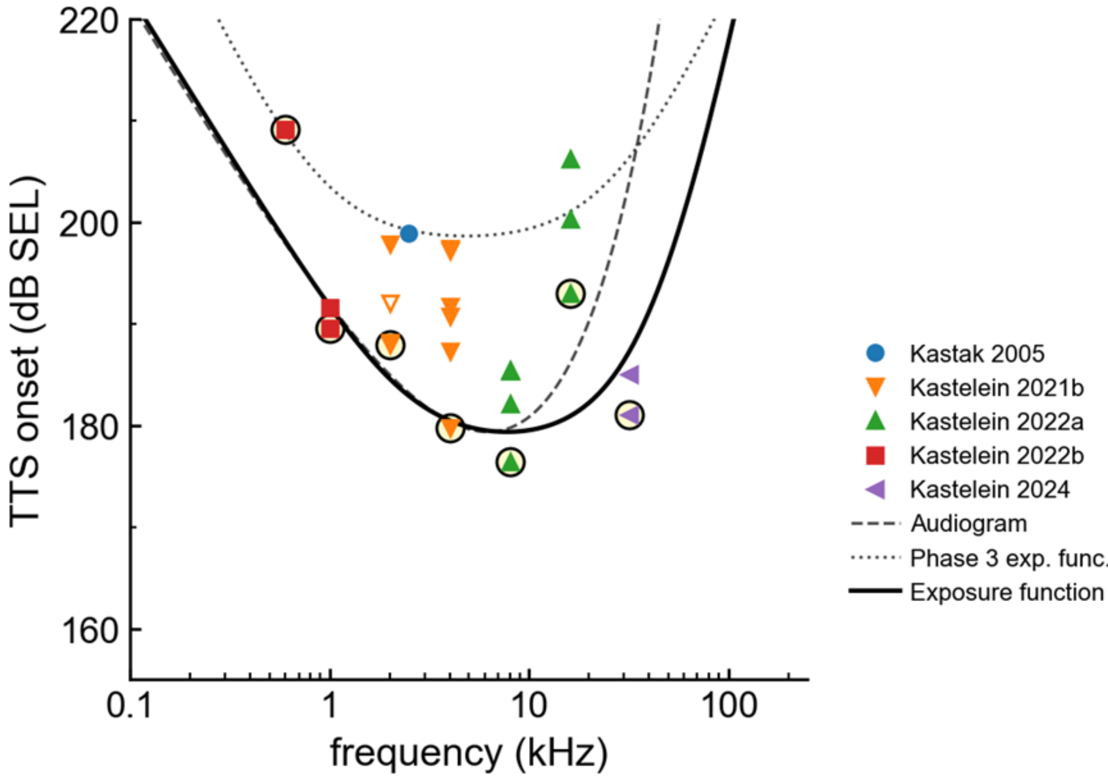

Figure A.17. **OCW non-impulsive exposure function, (normalized for display only) composite audiogram, and Phase 3 exposure function compared to OCW TTS data ≥ 6 dB. Filled symbols — onset TTS data (Appendix A.3). Open symbol — SEL producing TTS ≥ 6 dB for which TTS onset could not be determined. Large, yellow-filled circles indicate (mean) TTS onset values used during the fitting process.**

8. INJURY EXPOSURE FUNCTIONS FOR SONARS

As in previous acoustic effects analyses (Southall et al., 2007; Finneran and Jenkins, 2012; Southall et al., 2019), the shape of the INJ exposure function for each species group is assumed to be identical to the TTS exposure function for that group. Therefore, definition of the INJ function only requires the value for the constant *K* to be determined. This equates to identifying the increase in noise exposure between the onset of TTS and the onset INJ, defined here as an exposure producing 40 dB of TTS. For Navy Phase 3, a difference of 20 dB between TTS onset and INJ onset was used for all species groups. This was based on estimates of exposure levels required for 40 dB of TTS from the marine mammal TTS growth curves.

For Phase 4, the same approach was followed, with the inclusion of new published data. Tables A.3-1 to A.3-5 reveal differences of ~9 to 52 dB (mean = 23, median = 17, *n* = 12) between TTS onset and INJ onset (i.e., 40 dB TTS) in marine mammals. Figure A.18 shows the distribution of values. For simplicity and consistency with past approaches, Phase 4 utilizes a single value of 20 dB to estimate the difference between TTS onset and INJ onset for all species groups. The value of *K* for each INJ exposure function and the weighted INJ threshold were therefore determined by adding 20 dB to the *K*-value for the TTS exposure function or the TTS weighted threshold, respectively (see Table A.7).

For PCW, this 20 dB difference results in an INJ threshold of 195 dB re 1 μPa^{2}s at 4.1 kHz. This is 4 dB below the exposure SEL of 199 dB re 1 μPa^{2}s reported by Reichmuth et al. (2019) to result in PTS in a harbor seal. The Phase 4 PCW non-impulsive INJ criteria are therefore consistent with the harbor seal PTS data.

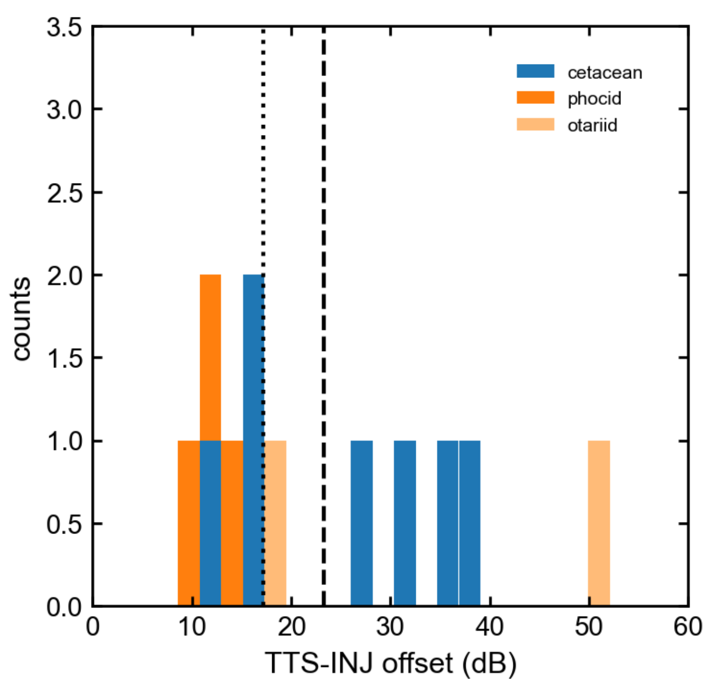

Figure A.18. Distribution of values indicating the increase in noise exposure between the onset of TTS and the onset INJ, based on marine mammal TTS growth curves with measured TTS ≥ 20 dB (Appendix A.3). The dotted and dashed lines show the median and mean values, 17 and 23 dB, respectively.

9. TTS/INJ EXPOSURE FUNCTIONS FOR EXPLOSIVES

The shapes of the TTS and INJ exposure functions for explosives and other impulsive sources are identical to those used for sonars and other active acoustic sources (i.e., steady-state or non-impulsive noise sources). Thus, defining the TTS and INJ functions only requires the values for the constant *K* to be determined.

Phase 4 analyses for TTS and INJ from underwater detonations and other impulsive sources follow previous approaches, where a weighted SEL threshold is used in conjunction with an unweighted peak SPL threshold (Southall et al., 2007; Finneran and Jenkins, 2012; National Marine Fisheries Service, 2016; Department of the Navy, 2017; National Marine Fisheries Service, 2018; Southall et al., 2019). The threshold producing the greater range for effect is used for estimating the effects of the noise exposure.

Peak SPL thresholds for TTS were based on TTS data from single impulsive sound exposures that produced 6 dB or more TTS for the HF and VHF groups (the only groups for which data are available). The peak SPL thresholds from these data were 224 and 196 dB re 1 μPa, for groups HF and VHF, respectively (Table A.5, Finneran et al., 2002; Lucke et al., 2009). Note the data from Sills et al. (2020b) and Mulsow et al. (2022) were not used to establish a peak SPL threshold for PCW and HF, respectively, since exposures with the same peak SPL did not always result in TTS when the number of impulses was reduced.

SEL thresholds for TTS were based on TTS data from single or multiple impulsive sound exposures that produced 6 dB or more TTS for the HF, VHF, and PCW groups (the only groups for which data are available). The SEL-based thresholds were determined by applying the Phase 4 weighting functions for the appropriate species groups to the exposure 1/3-octave frequency spectra that produced TTS, then calculating the resulting cumulataive weighted SELs. When this method is applied to the exposure data from Lucke et al. (2009) and Sills et al. (2020b), the cumulative weighted SEL TTS thresholds are 144 and 168 dB re 1 μPa^{2}s, respectively (Table A.5). For the HF group, cumulative weighted SELs for onset TTS were 175, 177, 178, and 188 dB re 1 μPa^{2}s (mean = 180, median = 178). Since the 188-dB value appears to be an outlier from the other three values, the median of 178 dB re 1 μPa^{2}s was therefore used as the SEL-based onset TTS for the HF group. Similarly, the median value for C_s - C_i (3.5 dB) was used for the HF group.

For species groups for which no impulse TTS data exist for TTS onset, the weighted SEL thresholds were estimated using the relationship between the steady-state TTS weighted threshold and the impulse TTS weighted threshold for the groups for which data exist (HF, VHF, PCW):

$$G_s - G_i = \overline{C_s - C_i}, \quad (6)$$

where *G* indicates thresholds for a species group for which impulse TTS data are not available, *C* indicates the threshold for the groups for which data exist, the subscript *s* indicates a steady-state threshold, the subscript *i* indicates an impulse threshold, and the overbar symbol (—) indicates the mean value. For groups HF, VHF, PCW, C_s - C_i = 3.5, 17, and 7.0 dB, respectively (mean = 9.2 dB). Therefore, for each of the remaining groups the SEL-based impulse TTS threshold is 9.2 dB below the steady-state (non-impulse) TTS threshold (Table A.9).

Table A.8. Summary of function parameters for use in Eqs. (1) and (2) to generate Phase 4 weighting functions and exposure functions, respectively. Values for *K* are rounded to the nearest dB.

Group	a	b	f_1 (kHz)	f_2 (kHz)	C (dB)	Non-impulse K_{TTS} (dB)	Non-impulse K_{INJ} (dB)	Impulse K_{TTS} (dB)	Impulse K_{INJ} (dB)
LF	0.990	5.00	0.168	26.6	0.120	177	197	168	183
HF	1.55	5.00	1.73	129	0.320	181	201	177	192
VHF	2.23	5.00	5.93	186	0.910	160	180	143	158
OCW	1.58	5.00	2.53	43.8	1.37	178	198	168	183
PCW	1.63	5.00	0.810	68.3	0.290	175	195	168	183
SI	1.66	5.00	5.91	37.6	3.61	176	196	167	182
OCA	1.35	5.00	1.75	32.5	1.18	156	176	147	162
PCA	2.05	5.00	0.739	24.4	0.830	133	153	124	139

To estimate peak SPL-based thresholds, the peak SPL “dynamic range” was defined as the difference (in dB) between the impulsive noise, peak SPL TTS onset (in dB re 1 μPa) and the hearing threshold at f_0 (in dB re 1 μPa) for the groups for which peak SPL TTS onset data are available (HF, VHF). For groups HF and VHF, dynamic ranges are 173 and 147 dB, respectively (mean, median = 160 dB). Therefore, for the remaining species groups, the impulsive peak SPL-based TTS thresholds were estimated by adding 160 dB to the hearing threshold at f_0 (Table 6).

Since marine mammal PTS/auditory injury data from impulsive noise exposures do not exist, onset-INJ levels were estimated by adding 15 dB to the SEL-based TTS threshold and adding 6 dB to the peak-pressure based thresholds. These relationships were derived by Southall et al. (2007) from impulse noise TTS growth rates in chinchillas, and utilized in subsequent analyses (Finneran and Jenkins, 2012; National Marine Fisheries Service, 2016; Department of the Navy, 2017; National Marine Fisheries Service, 2018; Southall et al., 2019). The appropriate frequency weighting function for each functional hearing group is applied only when using the SEL-based thresholds to predict INJ.

Figure A.19 illustrates the shapes of the various Phase 4 auditory weighting functions. Table A.8 summarizes the parameters necessary to calculate the weighting function and exposure function amplitudes. Table A.9 summarizes the weighted TTS and INJ thresholds.

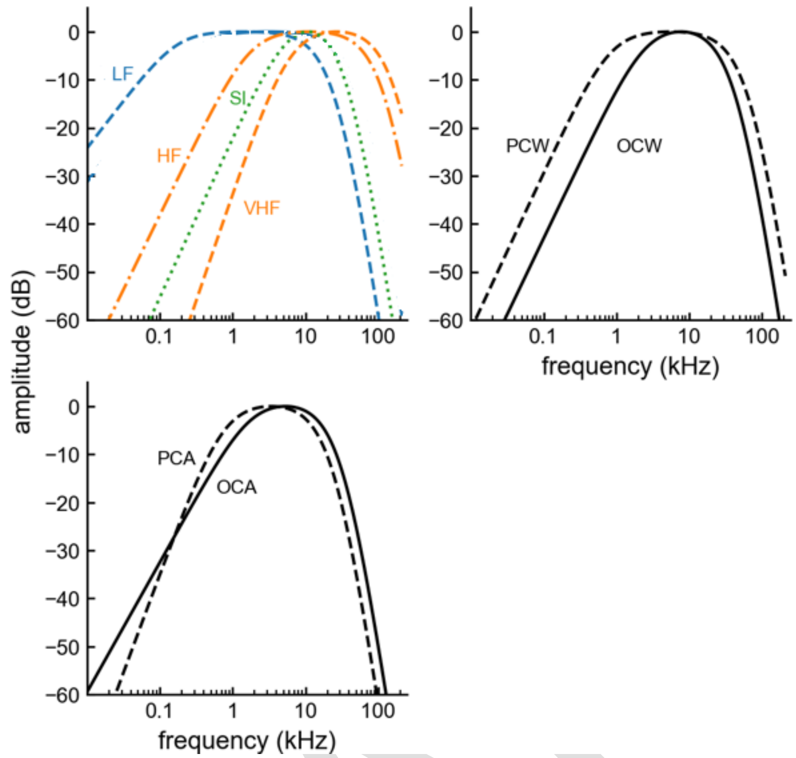

Figure A.19. **Navy Phase 4 weighting functions for all marine mammal species groups. Parameters required to generate the functions are provided in Table A.8.**

Table A.9. TTS and INJ thresholds for non-impulsive and impulsive sources*. SEL thresholds in dB re 1 μPa^{2}s underwater and dB re (20 μPa)^{2}s in air (groups OCA and PCA only). Peak SPL thresholds in dB re 1 μPa underwater and dB re 20 μPa in air (groups OCA and PCA only).

Group	Non-impulsive TTS threshold SEL (weighted)	Non-impulsive INJ threshold SEL (weighted)	Impulsive TTS threshold SEL (weighted)	Impulsive TTS threshold peak SPL (unweighted)	Impulsive INJ threshold SEL (weighted)	Impulsive INJ threshold peak SPL (unweighted)
LF	177	197	168	216	183	222
HF	181	201	178	224	193	230
VHF	161	181	144	196	159	202
OCW	179	199	170	224	185	230
PCW	175	195	168	217	183	223
SI	180	200	171	219	186	225
OCA	157	177	148	171	163	177
PCA	134	154	125	156	140	162

***NMFS added footnote**: Thresholds are determined from minimum value of auditory exposure function and the weighting function at its peak (i.e., mathematically equivalent to $K + C$) in Table A-8. However, it should be noted that only rounded values are presented in this Table, so for HFC and OCW, impulsive SEL thresholds do not appear to equal $K + C$, but in actuality, they do..

To properly compare the TTS/INJ criteria and thresholds used by Navy for Phase 3 and Phase 4, both the weighting function shape and weighted threshold values must be considered; the weighted thresholds by themselves only indicate the TTS/INJ threshold at the most susceptible frequency (based on the relevant weighting function). Since the exposure functions incorporate both the shape of the weighting function and the weighted threshold value, they provide the best means of comparing the frequency-dependent TTS/INJ thresholds for Phase 3 and 4 (Figs. A.20 and A.21).

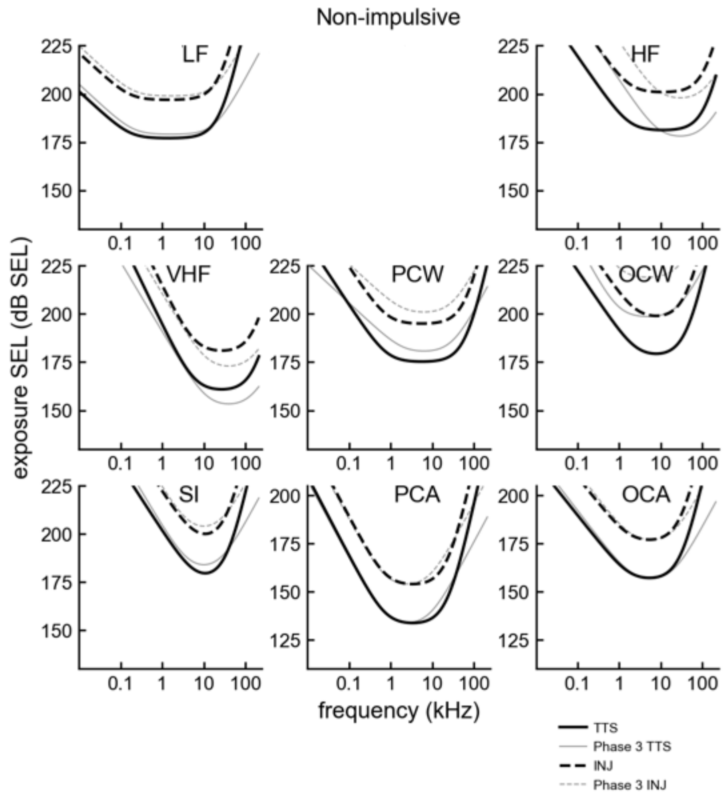

Figure A.20. **TTS and INJ exposure functions for sonars and other (non-impulsive) active acoustic sources (see Table 8 for function parameters). Heavy solid lines — Navy Phase 4 TTS exposure functions. Thin solid lines — Navy Phase 3 TTS exposure functions. Thick dashed lines — Navy Phase 4 INJ exposure functions. Thin dashed lines — Navy Phase 3 INJ exposure functions.**

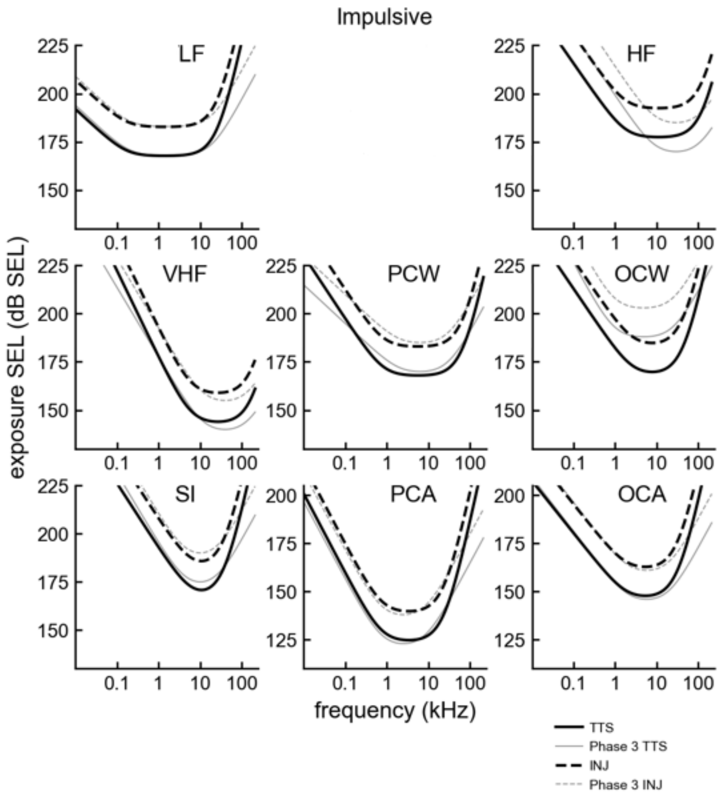

Figure A.21. TTS and INJ exposure functions for explosives, impact pile driving, air guns, and other impulsive sources (see Table 8 for function parameters). Heavy solid lines — Navy Phase 4 TTS exposure functions. Thin solid lines — Navy Phase 3 TTS exposure functions. Thick dashed lines — Navy Phase 4 INJ exposure functions. Thin dashed lines — Navy Phase 3 INJ exposure functions.

APPENDIX A.1 AUDIOGRAM DATA

Table A.1-1. Audiogram datasets used for creating composite audiograms.

Group	Species	Study	Animals	Notes
HF	*Delphinapterus leucas*	Awbrey 1988	Adult female	
			Kojak	1 kHz excluded (already in White 1978)
			Subadult male	
		Finneran 2005a	Beethoven	
		Johnson 1989	Female	
		Ridgway 2001	MUK	
			NOC	
		White 1978	Edwina	
			Kojak	
	Lagenorhynchus obliquidens	Tremel 1998	Female	
	Orcinus orca	Branstetter 2017	C	
			D	
			E	
			F	
			G	
			H	
		Szymanski 1999	Vigga	
			Yaka	
	Pseudorca crassidens	Thomas 1988	I'a nui hahai	
	Sotalia fluviatilis	Sauerland 1998	Paco	
	Stenella coeruleoalba	Kastelein 2003	ScSH001	
	Tursiops truncatus	Finneran 2010	TYH	
		Johnson 1967	Salty	
		Lemonds 2011	Itsi Bitsy	
VHF	*Inia geoffrensis*	Jacobs 1972	N/a	
	Phocoena phocoena	Kastelein 2002a	PpSH047	
		Kastelein 2010	Jerry (02)	
		Kastelein 2015a	ID No. 04	

Table A.1-1. (cont.)

Group	Species	Study	Animals	Notes
VHF	*Phocoena phocoena*	Kastelein 2017a	Pp05	
			Pp06	
SI	*Trichechus manatus latirostris*	Gaspard 2012	Buffet	
			Hugh	
		Gerstein 1999	Dundee	Excluded data below 400 Hz (tactile perception)
			Stormy	Excluded data below 400 Hz (tactile perception)
OCA	*Callorhinus ursinus*	Babushina 1991	N/a	
		Moore 1987	Lori	
			Tobe	
	Enhydra lutris nereis	Ghoul 2014	Charlie	
	Eumetopias jubatus	Mulsow 2010	Astro	
	Ursus maritimus	Owen 2011	SD Zoo	Mean of 2 animals
			Sea World SD	Mean of 3 animals
	Zalophus californianus	Moore 1987	Rocky	
		Mulsow 2011	JFN	
		Reichmuth 2013	Rio	
		Reichmuth 2017	Ronan	
OCW	*Callorhinus ursinus*	Babushina 1991	N/a	
		Moore 1987	Lori	
			Tobe	
	Enhydra lutris nereis	Ghoul 2014	Charlie	
	Eumetopias jubatus	Kastelein 2005	EjZH021	
			EjZH022	
	Odobenus rosmarus divergens	Kastelein 2002	OrZH 003 (Igor)	
	Zalophus californianus	Cunningham 2016	Ronan	50 kHz and above only
		Kastak 1998	Rocky	
		Kastelein 2023	F01	
			M02	

Table A.1-1. (cont.)

Group	Species	Study	Animals	Notes
OCW	*Zalophus californianus*	Reichmuth 2013	Ronan	
PCA	*Phoca largha*	Sills 2014	Amak	
			Tunu	
	Phoca vitulina	Reichmuth 2013	Sprouts	
	Pusa hispida	Sills 2015	Nayak	
PCW	*Erignathus barbatus*	Sills 2020a	Noatak	
			Siku	
	Mirounga angustirostris	Kastak 1999	Burnyce	
	Neomonachus schauinslandi	Sills 2021	Kekoa	
	Pagophilus groenlandicus	Terhune 1972	Female	
	Phoca largha	Cunningham 2016	Tunu	
		Sills 2014	Amak	
			Tunu	
	Phoca vitulina	Cunningham 2016	Sprouts	80 kHz and above only
		Kastelein 2009b	SM.Pv.01	
			SM.Pv.02	
		Reichmuth 2013	Sprouts	
		Terhune 1988	N/a	
	Pusa hispida	Sills 2015	Nayak	

Table A.1-2. Audiogram datasets available but not used for composite audiogram creation.

Group	Species	Study	Animals	Notes
HF	*Delphinapterus leucas*	Finneran 2005a	Turner	High-frequency hearing loss
	Grampus griseus	Nachtigall 1995	Hana	Suspected broadband hearing loss
	Orcinus orca	Branstetter 2017	A	Broadband hearing loss
			B	Low-frequency hearing loss
		Hall 1972	Subadult male	High-frequency hearing loss
	Pseudorca crassidens	Yuen 2005	Kina	High-frequency hearing loss
	Sotalia fluviatilis	Liebschner 2005	Paco	Tested in air
	Tursiops truncatus	Brill 2001	CAS	Thresholds masked by ambient noise
			HEP	High-frequency hearing loss
		Cook 2006	Ranier	Broadband hearing loss
		Finneran 2007	BLU	High-frequency hearing loss
		Schlundt 2007	WEN	Tested in air
	Tursiops truncatus gilli	Ljungblad 1982	12-y female	Aberrant audiogram
VHF	*Lipotes vexillifer*	Wang 1992	Qi Wi	High-frequency hearing loss
	Phocoena phocoena	Andersen 1970	N/a	Elevated thresholds near upper limit
SI	*Trichechus manatus latirostris*	Mann 2009	Buffet	Represented in Gaspard 2012
			Hugh	Represented in Gaspard 2012
OCA	*Odobenus rosmarus divergens*	Kastelein 1996	OrZH003 (Igor)	Thresholds appear masked
			OrZH003 (Igor)	Thresholds appear masked
	Zalophus californianus	Holt 2012	Rio	Represented in Reichmuth 2013
		Kastak 1998	Rocky	Elevated thresholds
		Schusterman 1974	Sam	Abberant audiogram shape for species
OCW		Cunningham 2016	Ronan	Data below 50 kHz excluded
		Kastak 1998	Rio	Data from Reichmuth 2012 used instead
		Kastak 2002	Newman	Elevated thresholds
		Schusterman 1972	Sam	Elevated thresholds
PCA	*Mirounga angustirostris*	Kastak 1998	Burnyce	Monachid thresholds very high re: other phocids
		Kastak 1999	Burnyce	Monachid thresholds very high re: other phocids

Table A.1-2. (cont.)

Group	Species	Study	Animals	Notes
PCA	*Mirounga angustirostris*	Reichmuth 2013	Burnyce	Monachid thresholds very high re: other phocids
	Neomonachus schauinslandi	Ruscher 2021	KE18	Monachid in-air thresholds very high re: other phocids
	Phoca vitulina	Kastak 1998	Sprouts	Represented in Reichmuth 2013
		Møhl 1968	3-4 y Male	Uncontrolled environment, elevated thresholds
		Wolski 2003	SWCPV9614B	Elevated thresholds near 2 kHz
			SWCPV9614B	Elevated thresholds
	Pusa caspica	Babushina 1997	Adult female	Elevated thresholds
	Pusa hispida	Sills 2015	Natchek	High-frequency hearing loss in underwater measurements
PCW	*Mirounga angustirostris*	Kastak 1998	Burnyce	Represented in Kastak 1999
	Monachus schauinslandi	Thomas 1990	Maka	Elevated thresholds below 10 kHz
	Phoca vitulina	Cunningham 2016	Sprouts	Data below 80 kHz represented in Reichmuth 2013
		Kastak 1998	Sprouts	Represented in Reichmuth 2013
		Kastelein 2009a	SM.Pv.01	Pure tone thresholds in Kastelein 2009b
			SM.Pv.02	Pure tone thresholds in Kastelein 2009b
		Møhl 1968	3-4 y Male	Elevated thresholds
	Pusa caspica	Babushina 1997	Adult female	Elevated thresholds
	Pusa hispida	Sills 2015	Natchek	High-frequency hearing loss
		Terhune 1975	Female	Elevated thresholds
			Male	Elevated thresholds

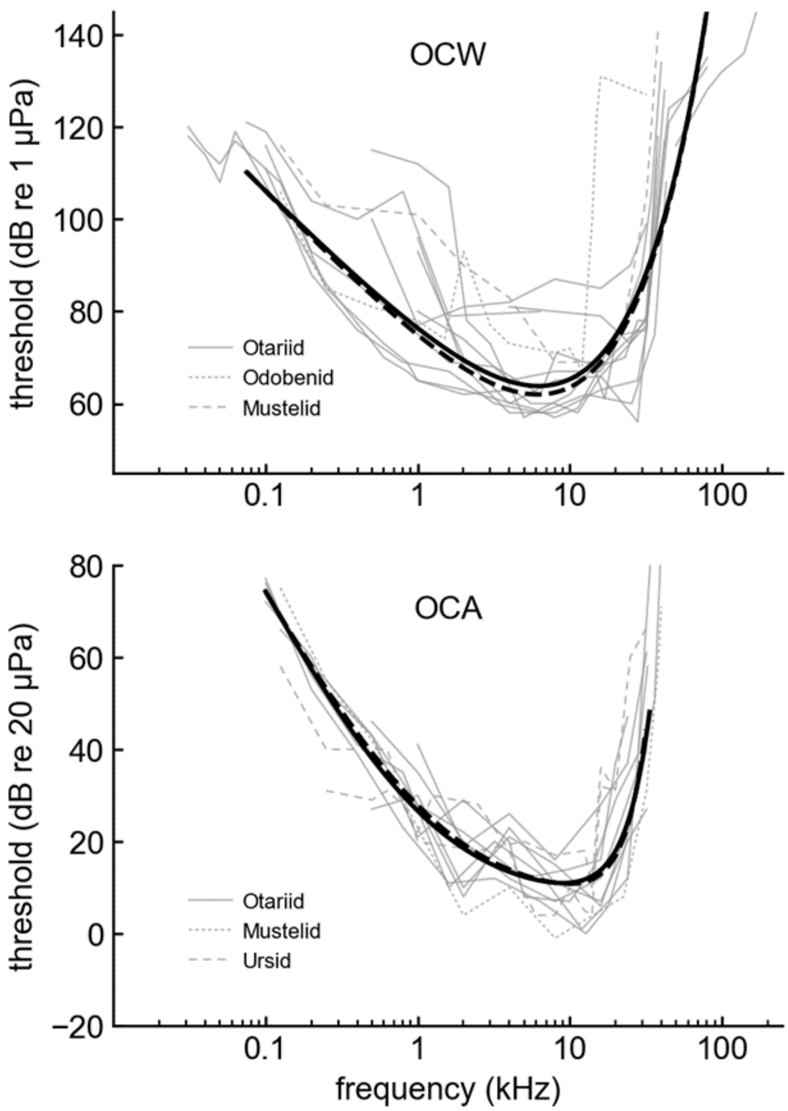

Figure A.1-1. **Comparison of Otariid, Mustelid, Odobenid, and Ursid psychophysical hearing thresholds measured underwater (top) and in-air (bottom). The thick, solid line is the composite audiogram based on data for all species. The thick, dashed line is the composite audiogram based on the otariids only.**

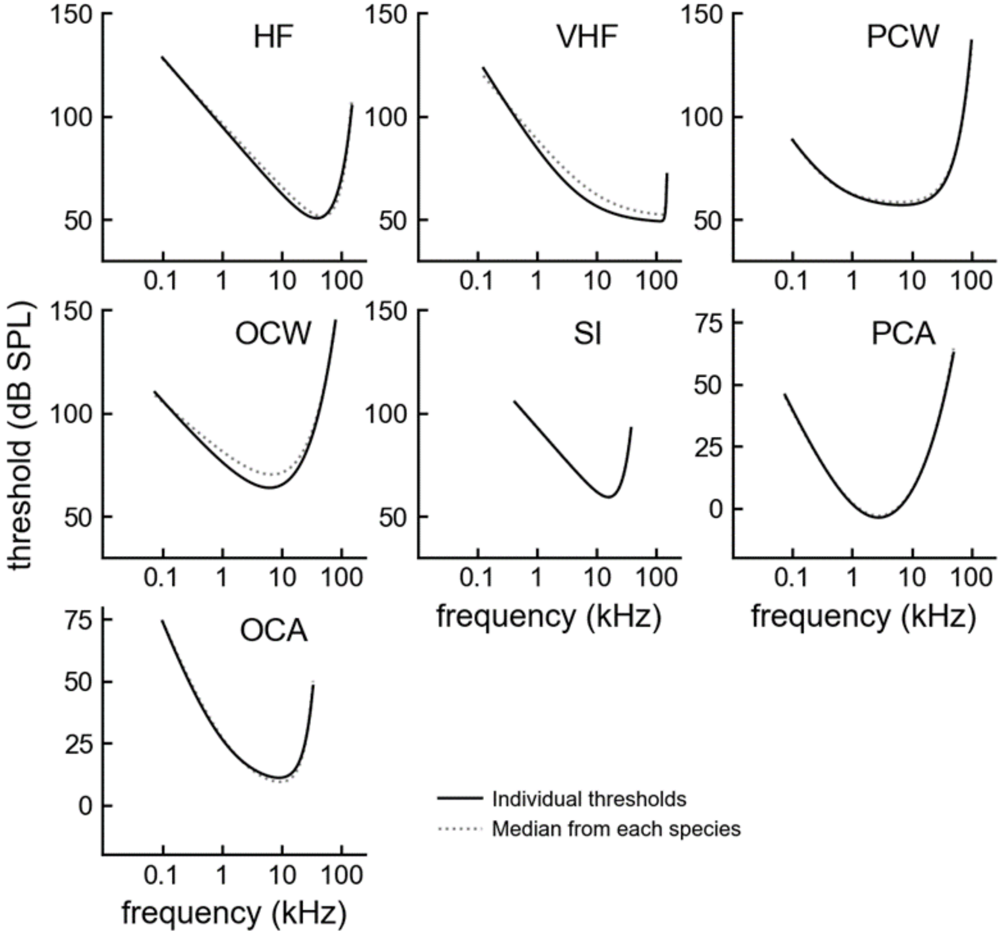

Figure A.1-2. Comparison of composite thresholds for groups with audiogram data. The thick, solid line is the composite audiogram based on the median of the individual threshold data. The dotted line is the composite audiogram based on the median of the thresholds for each species; i.e., the median threshold was first computed for each species, then the median of these data was computed.

APPENDIX A.2 ESTIMATING A LOW-FREQUENCY CETACEAN AUDIOGRAM

A.2.1. BACKGROUND

Psychophysical and/or electrophysiological auditory threshold data exist for at least one species within each hearing group, except for the mysticetes, for which auditory thresholds have not been directly measured. For this reason, composite audiograms for mysticetes must be estimated.

Mathematical models based on anatomical data have been used to predict hearing curves for several mysticete species (e.g., Ketten and Mountain, 2009; Cranford and Krysl, 2015). However, these predictions are not directly used to derive the Phase 4 composite mysticete audiograms because: (1) There are no peer-reviewed publications that provide a complete description of the process by which anatomical frequency-place maps were integrated with middle-ear transfer functions to predict the audiograms (e.g., Ketten and Mountain, 2009). (2) The fin whale model (Cranford and Krysl, 2015) does not include the sensory receptors of the inner ear, therefore the upper cutoff of hearing and audiogram shape above the region of best sensitivity cannot be predicted. Furthermore, the predicted audiogram does not possess the typical shape one would expect for an individual with normal hearing based on measurements from other mammals.

Vocalization data also cannot solely be used to estimate auditory thresholds and audible range, since there are many examples of mammals that vocalize with energy below the frequency range where they have best hearing sensitivity, and well below their upper frequency limit (UFL) of hearing (including cattle, dogs, and humans, see Heffner and Heffner, 1992). However, it is generally expected that animals have at least some degree of overlap between the auditory sensitivity curve and the predominant frequencies present in conspecific communication signals. Therefore, vocalization data can be used to evaluate, at least at a general level, whether the composite audiogram is reasonable; i.e., to ensure that the predicted thresholds make sense given what we know about animal vocalization frequencies, source levels, and communication range. Similarly, behavioral observations of animals reacting to sound playbacks can be used to evaluate the proposed audiogram, but cannot be used to directly derive the function, since it is impossible to know if the animals detected the sound but simply did not react (i.e., the data do not permit absolute sensitivity to be determined).

Given the limited nature of the available data, Phase 4 mysticete audiograms were estimated not from any one source but by synthesizing information from a variety of sources, including: cochlear frequency-place maps created from anatomical measurements of basilar membrane dimensions (e.g., Ketten, 1994; Parks et al., 2007); scaling relationships between mammalian inter-aural time differences and UFL (see Ketten, 2000); finite element models of head-related and middle-ear transfer functions (Tubelli et al., 2012; Cranford and Krysl, 2015); model-based predictions of relative hearing sensitivity for the humpback whale (Houser et al., 2001); measurements of the source levels and frequency content of mysticete vocalizations (see review by Tyack and Clark, 2000); and observations of mysticete reactions to sound playbacks (e.g., Kvadsheim et al., 2017; Boisseau et al., 2021). These data were then supplemented with extrapolations from the other marine mammal species groups where necessary.

A.2.2. AUDIOGRAM FUNCTIONAL FORM AND REQUIRED PARAMETERS

Composite audiograms are defined by the equation

$$T(f) = T_0 + A \log_{10}\left(1 + \frac{F_1}{f}\right) + \left(\frac{f}{F_2}\right)^B, \tag{A.2-1}$$

where $T(f)$ is the threshold at frequency f, and T_0, F_1, F_2, A, and B are constants. To understand the roles of the parameters T_0, F_1, F_2, A, and B, Eq. (A.2-1) may be viewed as the sum of three individual terms:

$$T_0 + L(f) + H(f), \tag{A.2-2}$$

where

$$L(f) = A \log_{10}\left(1 + \frac{F_1}{f}\right), \tag{A.2-3}$$

and

$$H(f) = \left(\frac{f}{F_2}\right)^B. \tag{A.2-4}$$

The first term, T_0, controls the vertical position of the curve; i.e., T_0 shifts the audiogram up and down.

The second term, $L(f)$, controls the low-frequency behavior of the audiogram. At low frequencies, when $f < F_1$, Eq. (A.2-3) approaches

$$L(f) = A \log_{10}\left(\frac{F_1}{f}\right), \tag{A.2-5}$$

which can also be written as

$$L(f) = A \log_{10} F_1 - A \log_{10} f. \tag{A.2-6}$$

Equation (A.2-6) has the form of $y(x) = b - Ax$, where $x = \log_{10}f$; i.e., Eq. (B-6) describes a linear function of the logarithm of frequency. This means that, as frequency gets smaller and smaller, Eq. (A.2-3) — the low-frequency portion of the audiogram function — approaches a linear function with the logarithm of frequency, and has a slope of $-A$ dB/decade. As frequency increases towards F_1, $L(f)$ asymptotically approaches zero.

The third term, $H(f)$, controls the high-frequency behavior of the audiogram. At low frequencies, when $f \ll F_2$, Eq. (B-4) has a value of zero. As f increases, $H(f)$ exponentially grows. The parameter F_2 defines the frequency at which the thresholds begin to exponentially increase, while the factor B controls the rate at which thresholds increase. Increasing F_2 will move the upper-cutoff frequency to the right (to higher frequencies). Increasing B will increase the “sharpness” of the high-frequency slope.

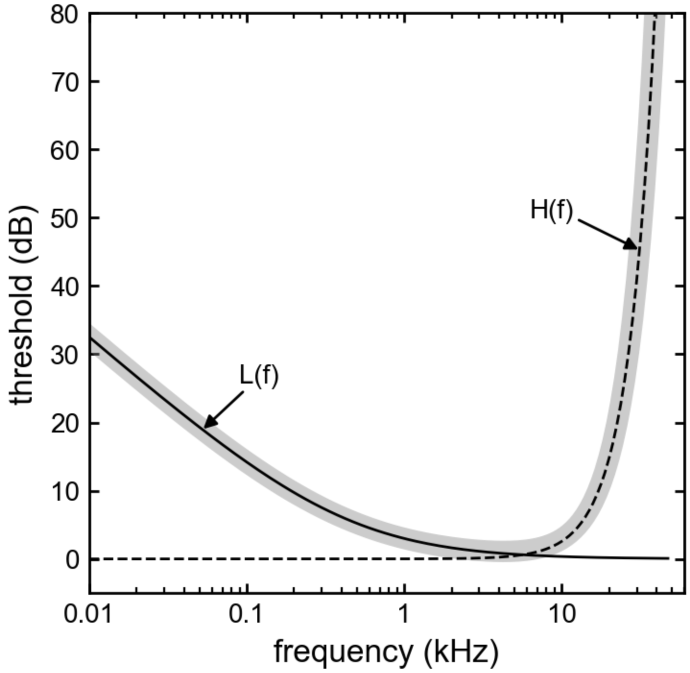

FIGURE A.2-1. Relationship between estimated threshold, T(f), (thick, gray line), low-frequency term, L(f), (solid line), and high-frequency term, H(f), (dashed line).

A.2.3. ESTIMATING AUDIOGRAM PARAMETERS

To derive a composite mysticete audiogram using Eq. (A.2-1), the values of T_0, F_1, F_2, A, and B must be defined. The constant A is defined by assuming a value for the low-frequency slope of the audiogram, in dB/decade. Most mammals for which thresholds have been measured have low-frequency slopes ~30 to 40 dB/decade. However, finite element models of middle ear function in fin whales (Cranford and Krysl, 2015) and minke whales (Tubelli et al., 2012) suggest lower slopes, of ~25 or 20 dB/decade, respectively. **We therefore conservatively assume that *A* = 20 dB/decade.**

To define F_1, we first define the variable T' as the maximum threshold tolerance within the frequency region of best sensitivity (i.e., within the frequency range of best sensitivity, thresholds are within T' dB of the lowest threshold). Further, let f' be the lower frequency bound of the region of best sensitivity. When $f = f'$, $L(f) = T'$, and Eq. (A.2-3) can then be solved for F_1 as a function of f', T', and A:

$$F_1 = f'\left(10^{T'/A} - 1\right). \qquad \text{(A.2-7)}$$

Anatomically based models of mysticete hearing have resulted in various estimates for audible frequency ranges and frequencies of best sensitivity. Houser et al. (2001) estimated best sensitivity in humpback whales to occur in the range of 2 to 6 kHz, with thresholds within 3 dB of best sensitivity from ~1.4 to 7.8 kHz. For right whales, Parks et al. (2007) estimated the audible frequency range to be 10 Hz to 22 kHz. For minke whales, Tubelli et al. (2012) estimated the most sensitive hearing range, defined as the region with thresholds within 40 dB of best sensitivity, to extend from 30 to 100 Hz up to 7.5 to 25 kHz, depending on the specific model used. Cranford and Krysl (2015) predicted best sensitivity in fin whales to occur at 1.2 kHz, with thresholds within 3-dB of best sensitivity from ~1 to 1.5 kHz. Together, these model results broadly suggest best sensitivity (thresholds within ~3 dB of the lowest threshold) from ~1 to 8 kHz, and thresholds within ~40 dB of best sensitivity as low as ~30 Hz and up to ~25 kHz.

Based on this information, we assume LF cetacean thresholds are within 3 dB of the lowest threshold over a frequency range of 1 to 8 kHz, therefore T' = 3 dB and f' = 1 kHz, resulting in **F_1 = 0.412 kHz** [Eq. (A.2.7)]. In other words, we define F_1 so that thresholds are ≤ 3 dB relative to the lowest threshold when the frequency is within the region of best sensitivity (1 to 8 kHz).

To define the high-frequency portion of the audiogram, the values of B and F_2 must be estimated. To estimate B for LF cetaceans, the median of the B values from the composite audiograms for the other in-water species groups is used (HF=1.66, VHF=24.5, SI=2.5, OCW=0.786, and PCW=1.79). **This results in B = 1.79 for the LF cetaceans.**

Once B is defined, F_2 is adjusted to achieve a threshold value at 30 kHz of 40 dB relative to the lowest threshold. **This results in F_2 = 3.73 kHz.**

Finally, T_0 is adjusted to set the lowest threshold value from the composite audiogram to a specific SPL. For Navy Phase 4 analyses, the lowest LF cetacean threshold is matched to the mean threshold of the in-water marine mammal species groups (HF, VHF, SI, OCW, PCW; mean = 56 dB re 1 μPa); this results in **T_0 = 54.2 dB.**

The resulting composite audiograms are shown in Fig. A.2-2. For comparison, predicted audiograms for the fin whale (Cranford and Krysl, 2015), and humpback whale (Houser et al., 2001) are included. The LF cetacean composite audiogram has lowest threshold at 2.8 kHz, but the audiogram is fairly shallow in the region of best sensitivity and thresholds are within 3 dB of the lowest threshold from ~0.55 to 8.5 kHz. Low-frequency (< ~500 Hz) thresholds are considerably lower than those predicted by Cranford and Krysl (2015). High-frequency thresholds are also substantially lower than those predicted for the fin whale, with thresholds at 30 kHz only 40 dB above best hearing thresholds, and those at 40 kHz approximately 70 dB above best threshold. The resulting composite audiogram appear reasonable considering the predominant frequencies present in mysticete conspecific vocal communication signals. While some species (e.g., blue whales) produce some extremely low (e.g., 10 Hz) frequency call components, the majority of mysticete calls occur in the range of a few tens of Hz to a few kHz , overlapping reasonably well with the predicted auditory sensitivity shown in the composite audiograms (within ~0 to 30 dB of predicted best sensitivity). A general pattern of some vocalizations containing energy shifted below the region of best hearing sensitivity is well-documented in other low-frequency species including many phocid seals (see Wartzok and Ketten, 1999), Steller sea lions (Mulsow and Reichmuth, 2010), and some terrestrial mammals, notably the Indian elephant (Heffner and Heffner, 1982; Heffner and Heffner, 1992).

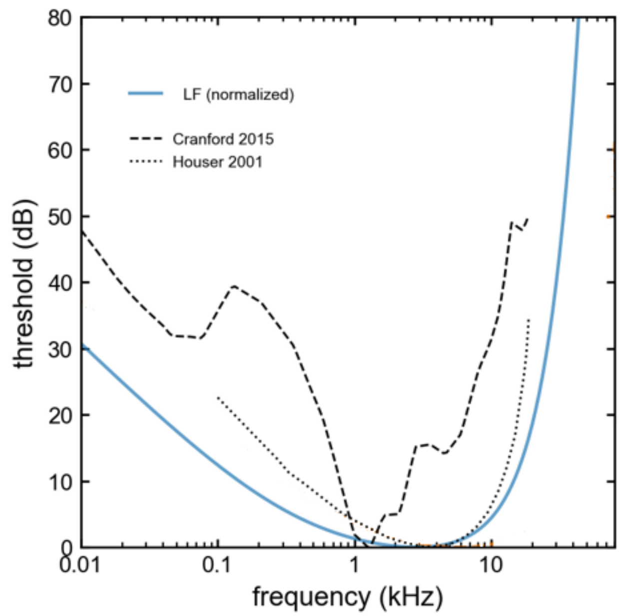

FIGURE A.2-2. Comparison of proposed LF cetacean thresholds to those predicted by anatomical and finite-element models.

APPENDIX A.3 MARINE MAMMAL TTS GROWTH CURVES

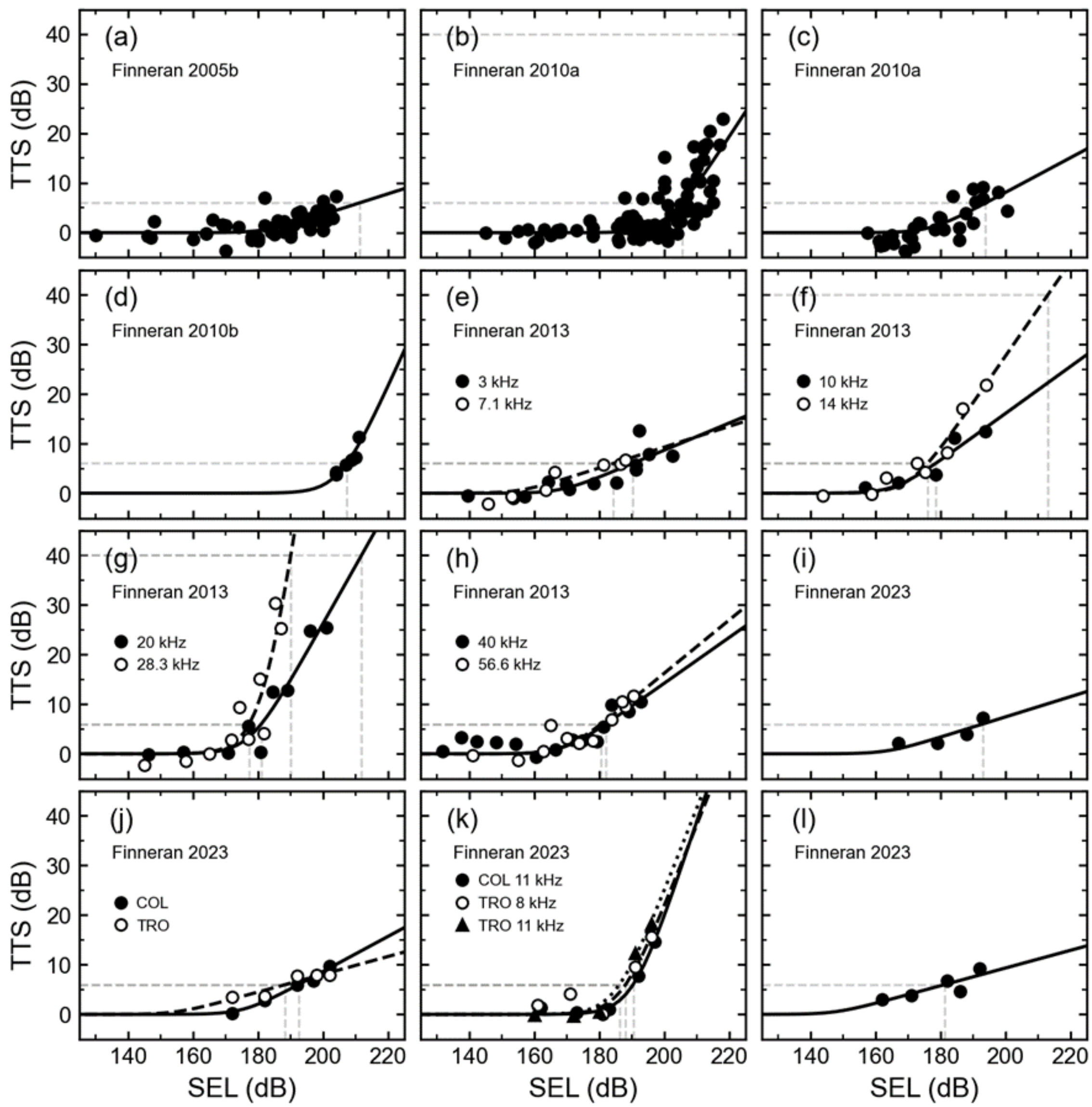

Figure A.3-1. TTS growth data for HF cetaceans obtained using behavioral methods. Growth curves were obtained by fitting Eq. (4) to the TTS data as a function of SEL. Onset TTS was defined as the SEL value from the fitted curve at TTS = 6 dB (shown with light gray dashed lines), for only those datasets that bracketed 6 dB of TTS. Onset INJ was defined as the SEL value from the fitted curve at a TTS = 40 dB, for only those datasets with maximum TTS > 20 dB. Solid lines are fit to the filled circles, dashed lines are fit to the open circles, and the dotted line is fit to the triangles. See Table A.3-1 for explanation of the datasets in each panel. SEL units are dB re 1 μPa²s.

Table A.3-1. Summary of group HF TTS growth data and onset exposure levels. Only those data from which growth curves could be generated are included. TTS onset values are expressed in SEL, in dB re 1 μPa²s. Tests featured exposure to steady-state noise and behavioral threshold measurements. "Panel" refers to corresponding sub-panel plot within Figure A.3-1.

Group	Species	Study	Subject	Exp. Freq. (kHz)	Hear. Freq. (kHz)	Min TTS (dB)	Max TTS (dB)	TTS onset (dB SEL)	TTS growth rate (dB/dB)	INJ onset (dB SEL)	INJ-TTS offset (dB)	Notes	Panel
HF	*Tursiops truncatus*	Finneran 2005b	BEN	3	4.5	0	7.4	211**	0.21	—	—	TTS onset higher than subsequent tests	(a)
		Finneran 2010a	BLU	3	4.5	0	23	206**	1	241	35	TTS onset higher than subsequent tests	(b)
			TYH	3	4.5	0	9.1	194	0.35	—	—	—	(c)
		Finneran 2010b	BLU	3	4.5	3.8	11	207**	1.5	—	—	Intermittent	(d)
		Finneran 2013	BLU	3	4.5	0	13	190	0.27	—	—	—	(e)
				7.1	10	0	6.7	184	0.21	—	—	—	(e)
				10	14	1.2	12	178	0.47	—	—	—	(f)
				14.1	20	0	22	176	0.95	213	37	—	(f)
				20	30	0	25	181	1.2	212	31	—	(g)
				28.3	40	0	30	177	4.5	190	13	—	(g)

Table A.3-1. (cont.)

Group	Species	Study	Subject	Exp. Freq. (kHz)	Hear. Freq. (kHz)	Min TTS (dB)	Max TTS (dB)	TTS onset (dB SEL)	TTS growth rate (dB/dB)	INJ onset (dB SEL)	INJ-TTS offset (dB)	Notes	Panel
HF	*Tursiops truncatus*	Finneran 2013	TYH	40	56.6	0	10	182	0.46	—	—	—	(h)
				56.6	80	0	12	181	0.54	—	—	—	(h)
		Finneran 2023	COL	0.5	0.5	2.2	7.2	193	0.2	—	—	—	(i)
				2	2	0.2	9.8	192	0.35	—	—	—	(j)
				8	11.3	0.4	15	190	2	—	—	—	(k)
			TRO	2	2	3.5	7.9	188	0.18	—	—	—	(j)
				8	8	0.1	16	188**	1.7	—	—	Lower TTS onset at 11 kHz	(k)
				8	11.3	0	18	186	1.7	—	—	—	(k)
				20	20	3	9.3	181	0.18	—	—	—	(l)

** Data excluded from mean onset TTS calculation. Reasons for exclusion include: (i) another data set resulted in a lower onset TTS at the same frequency, (ii) the data set featured a duty cycle less than 100%, (iii) TTS values were measured at times significantly larger than 4 min, (iv) a lower TTS onset was found at a different hearing test frequency (also see Notes).

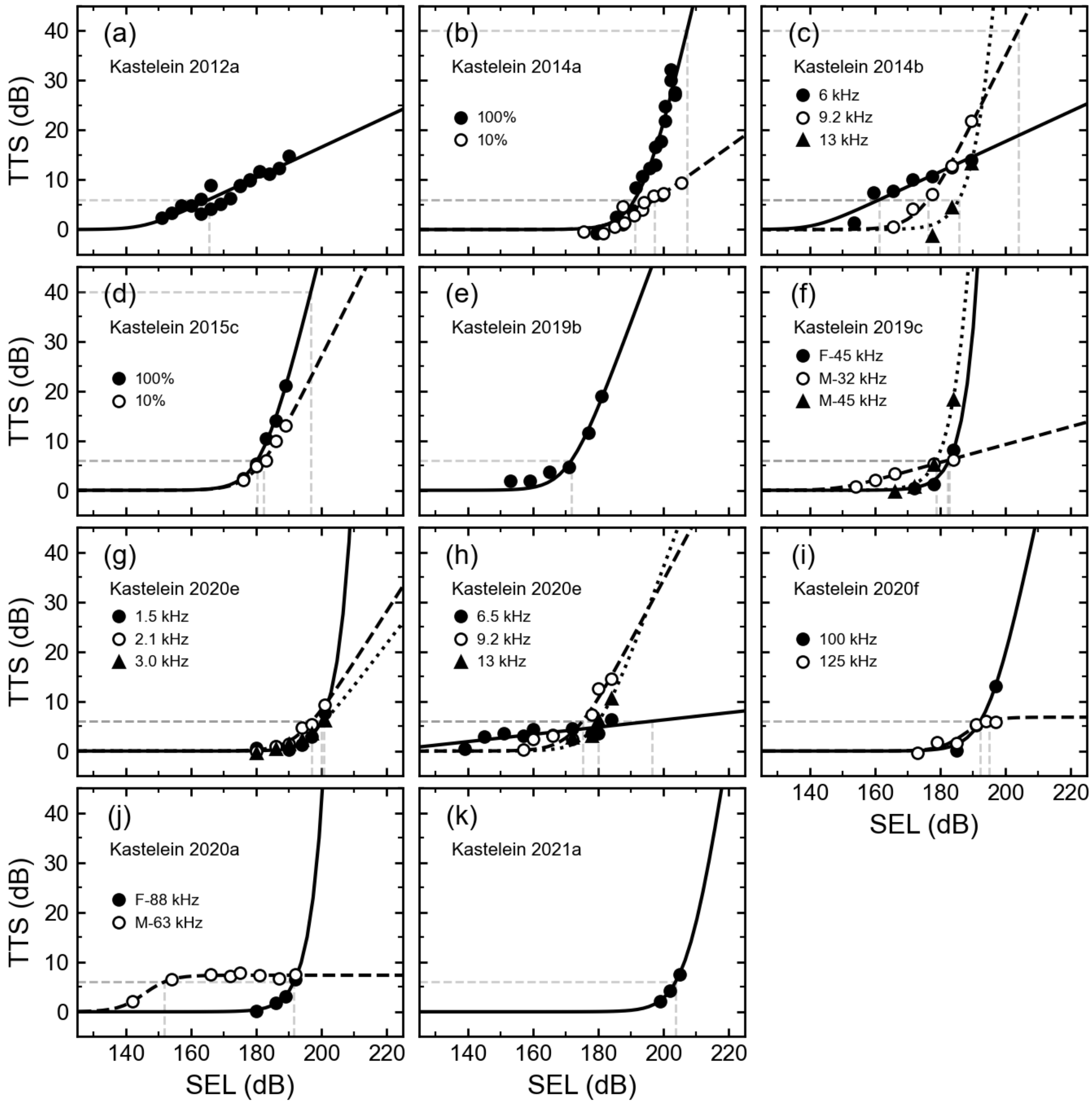

Figure A.3-2. TTS growth data for VHF cetaceans obtained using behavioral methods. Growth curves were obtained by fitting Eq. (4) or (5) to the TTS data as a function of SEL. Onset TTS was defined as the SEL value from the fitted curve at TTS = 6 dB, for only those datasets that bracketed 6 dB of TTS. Onset INJ was defined as the SEL value from the fitted curve at a TTS = 40 dB, for only those datasets with maximum TTS > 20 dB. Solid lines are fit to the filled circles, dashed lines are fit to the open circles, and dotted lines fit to the triangles. See Table A.3-2 for explanation of the datasets in each panel. SEL units are dB re 1 μPa^{2}s.

Table A.3-2. Summary of group VHF TTS growth data and onset exposure levels. Only those data from which growth curves could be generated are included. TTS onset values are expressed in SEL, in dB re 1 µPa²s. Tests featured continuous exposure to steady-state noise and behavioral threshold measurements. "Panel" refers to corresponding sub-panel plot within Figure A.3-2.

Group	Species	Study	Subject	Exp. Freq. (kHz)	Hear. Freq. (kHz)	Min TTS (dB)	Max TTS (dB)	TTS onset (dB SEL)	TTS growth rate (dB/dB)	INJ onset (dB SEL)	INJ-TTS offset (dB)	Notes	Panel
VHF	*Phocoena phocoena*	Kastelein 2012a	2	4	4	2.4	15	165	0.31	—	—	—	(a)
		Kastelein 2014a	2	1.5	1.5	0	32	191	2.8	207	16	100% duty cycle	(b)
				1.5	1.5	0	9.4	197**	0.47	—	—	10% duty cycle	(b)
		Kastelein 2014b	2	6.5	6.5	1.4	14	161	0.3	—	—	—	(c)
				6.5	9.2	0.5	22	176**	1.3	204	28	TTS onset at lower SEL at 6.5 kHz	(c)
				6.5	13	0	13	186**	11	—	—	TTS onset at lower SEL at 6.5 kHz	(c)
		Kastelein 2015c	2	6.5	9.2	2.3	21	180**	2.7	197	17	Same subject, higher TTS onset re: Kastelein 2014a	(d)
				6.5	9.2	2	13	182**	1.3	—	—	10% duty cycle	(d)
		Kastelein 2019b	M06	16	22.4	1.9	19	172*	1.8	—	—	—	(e)
		Kastelein 2019c	F05	32	44.8	0.4	8.2	183**	8.7×10^3	—	—	16-min post-exposure testing	(f)

Table A.3-2. cont.

Group	Species	Study	Subject	Exp. Freq. (kHz)	Hear. Freq. (kHz)	Min TTS (dB)	Max TTS (dB)	TTS onset (dB SEL)	TTS growth rate (dB/dB)	INJ onset (dB SEL)	INJ-TTS offset (dB)	Notes	Panel
VHF	*Phocoena phocoena*	Kastelein 2019c	M06	32	32	0.8	6.1	182**	0.18	—	—	Lower TTS onset at 44.8 kHz	(f)
				32	44.8	0	18	179*	19	—	—	—	(f)
		Kastelein 2020a	F05	63	88.4	0.2	6.6	192*	1.2×10^{3}	—	—	—	(j)
			M06	63	63	2.1	7.8	152*	—	—	—	—	(j)
		Kastelein 2020e	F05	1.5	1.5	0.2	7.6	200**	2.4×10^{3}	—	—	Lower TTS onset at 2.1 kHz	(g)
				1.5	2.1	0	9.3	197	1	—	—	—	(g)
				1.5	3	0	6.2	201**	0.85	—	—	Lower TTS onset at 2.1 kHz	(g)
				6.5	6.5	0.5	6.4	196**	0.07	—	—	Lower TTS onset at 9.2 kHz	(h)
				6.5	9.2	0.3	15	175	1.2	—	—	—	(h)
				6.5	13	2.7	11	180**	1.8	—	—	Lower TTS onset at 9.2 kHz	(h)

Table A.3-2. cont.

Group	Species	Study	Subject	Exp. Freq. (kHz)	Hear. Freq. (kHz)	Min TTS (dB)	Max TTS (dB)	TTS onset (dB SEL)	TTS growth rate (dB/dB)	INJ onset (dB SEL)	INJ-TTS offset (dB)	Notes	Panel
VHF	*Phocoena phocoena*	Kastelein 2020f	F05	88.4	100	0.1	13	192*	3.1	—	—	—	(i)
				88.4	125	0	6.1	195**	—	—	—	Lower TTS onset at 100 kHz	(i)
		Kastelein 2021a	F05	0.5	0.5	2.1	7.6	204	4.4	—	—	—	(k)

* SELs not used during exposure function fitting process.

** Data excluded from mean onset TTS calculation. Reasons for exclusion include: (i) another data set resulted in a lower onset TTS at the same frequency, (ii) the data set featured a duty cycle less than 100%, (iii) TTS values were measured at times significantly larger than 4 min, (iv) a lower TTS onset was found at a different hearing test frequency (also see Notes).

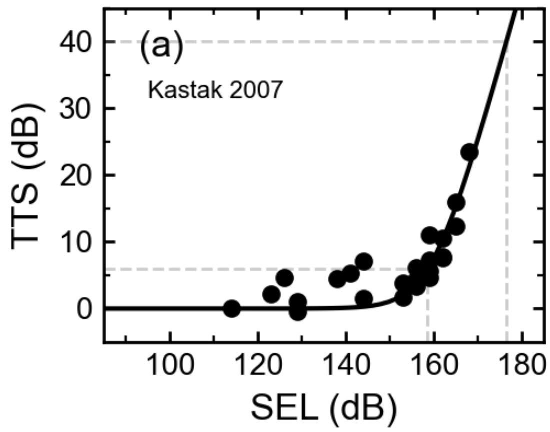

Figure A.3-3. TTS growth data for group OCA obtained using behavioral methods. The growth curve was obtained by fitting Eq. (4) to the TTS data as a function of SEL. Onset TTS was defined as the SEL value from the fitted curve at TTS = 6 dB. Onset INJ was defined as the SEL value from the fitted curve at a TTS = 40 dB. See Table A.3-3 for explanation of the dataset. SEL units are dB re (20 μPa)^{2}s.

Table A.3-3. Summary of group OCA TTS growth data and onset exposure levels. TTS onset values are expressed in SEL, in dB re (20 μPa)^{2}s. Tests featured continuous exposure to steady-state noise and behavioral threshold measurements.

Group	Species	Study	Subject	Exp. Freq. (kHz)	Hear. Freq. (kHz)	Min TTS (dB)	Max TTS (dB)	TTS onset (dB SEL)	TTS growth rate (dB/dB)	INJ onset (dB SEL)	INJ-TTS offset (dB)	Notes	Panel
OCA	*Zalophus californianus*	Kastak 2007	Rio	2.5	2.5	0	24	159	2.4	176	18	—	(a)

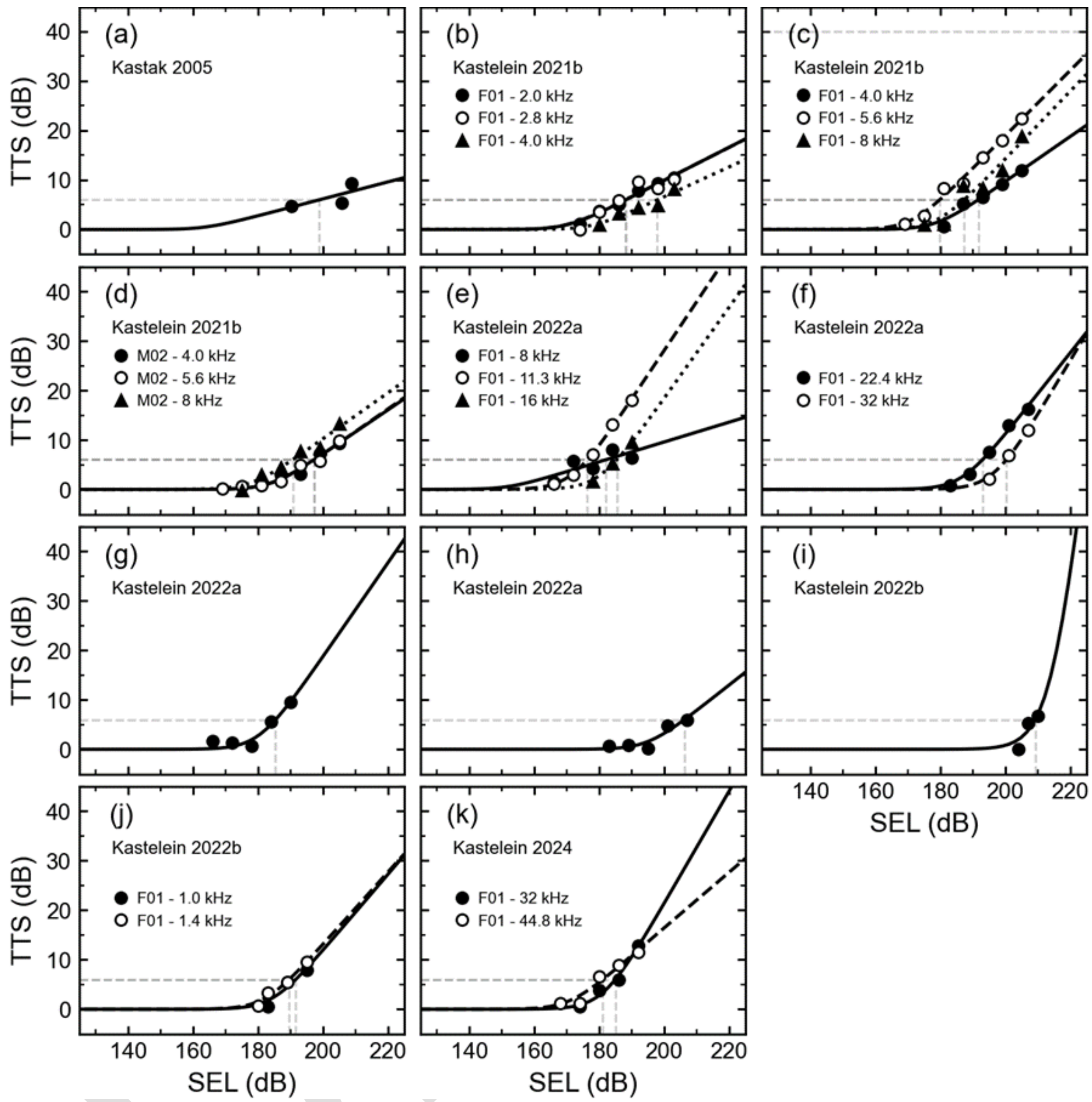

Figure A.3-4. **TTS growth data for group OCW obtained using behavioral methods. Growth curves were obtained by fitting Eq. (4) to the TTS data as a function of SEL. Onset TTS was defined as the SEL value from the fitted curve at TTS = 6 dB, for only those datasets that bracketed 6 dB of TTS. Onset INJ was defined as the SEL value from the fitted curve at a TTS = 40 dB, for only those datasets with maximum TTS > 20 dB. Solid lines are fit to the filled circles, dashed lines are fit to the open circles, and dotted lines fit to the triangles. See Table A.3-4 for explanation of the datasets in each panel. SEL units are dB re 1 μPa²s.**

Table A.3-4. Summary of group OCW TTS growth data and onset exposure levels. Only those data from which growth curves could be generated are included. TTS onset values are expressed in SEL, in dB re 1 $\mu Pa^2 s$. Tests featured continuous exposure to steady-state noise and behavioral threshold measurements. "Panel" refers to corresponding sub-panel plot within Figure A.3-4.

Group	Species	Study	Subject	Exp. Freq. (kHz)	Hear. Freq. (kHz)	Min TTS (dB)	Max TTS (dB)	TTS onset (dB SEL)	TTS growth rate (dB/dB)	INJ onset (dB SEL)	INJ-TTS offset (dB)	Notes	Panel
OCW	*Zalophus californianus*	Kastak 2005	Rio	2.5	2.5	4.8	9.3	199**	0.17	—	—	TTS measured 15 min post-exposure	(a)
		Kastelein 2021b	F01	2	2	1.2	10	188**	0.33	—	—	Lower TTS onset at 2.8 kHz	(b)
				2	2.8	0	10	188	0.33	—	—	—	(b)
				2	4	0.9	8.2	198**	0.3	—	—	Lower TTS onset at 2.8 kHz	(b)
				4	4.2	0.6	12	192**	0.45	—	—	Lower TTS onset at 5.6 kHz	(c)
				4	5.6	1.2	22	180	0.66	232	52	—	(c)
				4	8	1	19	187**	0.68	—	—	Lower TTS onset at 5.6 kHz	(c)
			M02	4	4.2	1	9.4	197**	0.45	—	—	TTS measured 12-16 min post-exposure	(d)
				4	5.6	0.2	9.8	197**	0.46	—	—	TTS measured 12-16 min post-exposure	(d)
				4	8	0	13	191**	0.46	—	—	TTS measured 12-16 min post-exposure	(d)

Table A.3-4. (cont.)

Group	Species	Study	Subject	Exp. Freq. (kHz)	Hear. Freq. (kHz)	Min TTS (dB)	Max TTS (dB)	TTS onset (dB SEL)	TTS growth rate (dB/dB)	INJ onset (dB SEL)	INJ-TTS offset (dB)	Notes	Panel
OCW	*Zalophus californianus*	Kastelein 2022a	F01	8	8	1.5	8	182**	0.2	—	—	Lower TTS onset at 11.3 kHz	(e)
				8	11.3	1.2	18	176	0.98	—	—	—	(e)
				8	16	1.7	9.5	186**	0.92	—	—	Lower TTS onset at 11.3 kHz	(e)
				16	22.4	0.8	16	193	0.83	—	—	—	(f)
				16	32	2.2	12	200**	1.1	—	—	Lower TTS onset at 22.4 kHz	(f)
			M02	8	11.3	0.7	9.5	185**	0.95	—	—	TTS measured 12-16 min post-exposure	(g)
				16	22.4	0.2	6	206**	0.52	—	—	TTS measured 12-16 min post-exposure	(h)
		Kastelein 2022b	F01	0.6	0.85	0.1	6.7	209	5.7	—	—	—	(i)
				1	1	0.5	8	192**	0.77	—	—	Lower TTS onset at 1.4 kHz	(j)
				1	1.4	0.7	9.6	190	0.73	—	—	—	(j)

Table A.3-4. (cont.)

Group	Species	Study	Subject	Exp. Freq. (kHz)	Hear. Freq. (kHz)	Min TTS (dB)	Max TTS (dB)	TTS onset (dB SEL)	TTS growth rate (dB/dB)	INJ onset (dB SEL)	INJ-TTS offset (dB)	Notes	Panel
OCW	*Zalophus californianus*	Kastelein 2024	F01	32	32	0.6	13	185**	1.1	—	—	lowest TTS onset at 44.8 kHz	(k)
				32	44.8	1.2	12	181	0.56	—	—	—	(k)

** Data excluded from mean onset TTS calculation. Reasons for exclusion include: (i) another data set resulted in a lower onset TTS at the same frequency, (ii) the data set featured a duty cycle less than 100%, (iii) TTS values were measured at times significantly larger than 4 min, (iv) a lower TTS onset was found at a different hearing test frequency (also see Notes).

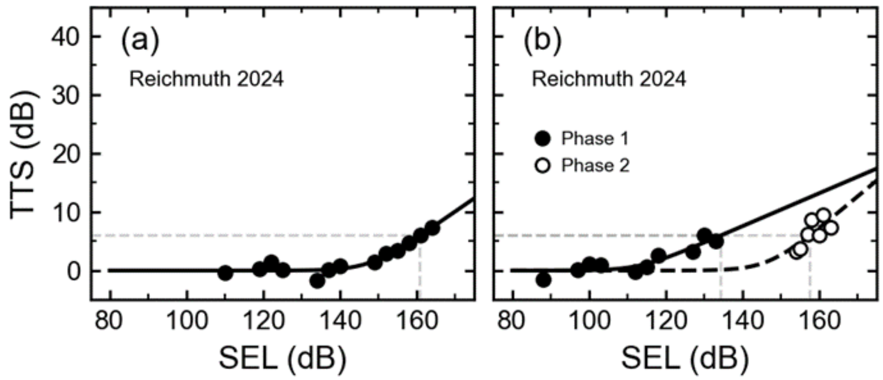

Figure A.3-5. TTS growth data for group PCA obtained using behavioral methods. Growth curves were obtained by fitting Eq. (4) to the TTS data as a function of SEL. Onset TTS was defined as the SEL value from the fitted curve at TTS = 6 dB, for only those datasets that bracketed 6 dB of TTS. Solid lines are fit to the filled circles, dashed lines are fit to the open circles. See Table A.3-5 for explanation of the datasets in each panel. SEL units are dB re (20 μPa)^{2}s.

Table A.3-5. Summary of group PCA TTS growth data and onset exposure levels. Only those data from which growth curves could be generated are included. TTS onset values are expressed in SEL, in dB re (20 μPa)^{2}s. Tests featured exposure to steady-state noise and behavioral threshold measurements. "Panel" refers to corresponding sub-panel plot within Figure A.3-5.

Group	Species	Study	Subject	Exp. Freq. (kHz)	Hear. Freq. (kHz)	Min TTS (dB)	Max TTS (dB)	TTS onset (dB SEL)	TTS growth rate (dB/dB)	INJ onset (dB SEL)	INJ-TTS offset (dB)	Notes	Panel
PCA	*Mirounga angustirostris*	Reichmuth 2024	Burnyce	1	1	0	7.4	161*	0.45	—	—	Data averaged by SEL. Much higher TTS onset than harbor seal at nearby frequency	(a)
	Phoca vitulina	Reichmuth 2024	Sprouts	2.5	2.5	0	6	134	0.28	—	—	Phase 1. Data averaged by SEL	(b)
				2.5	2.5	3.2	9.5	158**	0.55	—	—	Phase 2. Data averaged by SEL. Lower TTS onset during Phase 1 testing	(b)

* SELs not used during exposure function fitting process.

** Data excluded from mean onset TTS calculation. Reasons for exclusion include: (i) another data set resulted in a lower onset TTS at the same frequency, (ii) the data set featured a duty cycle less than 100%, (iii) TTS values were measured at times significantly larger than 4 min, (iv) a lower TTS onset was found at a different hearing test frequency (also see Notes).

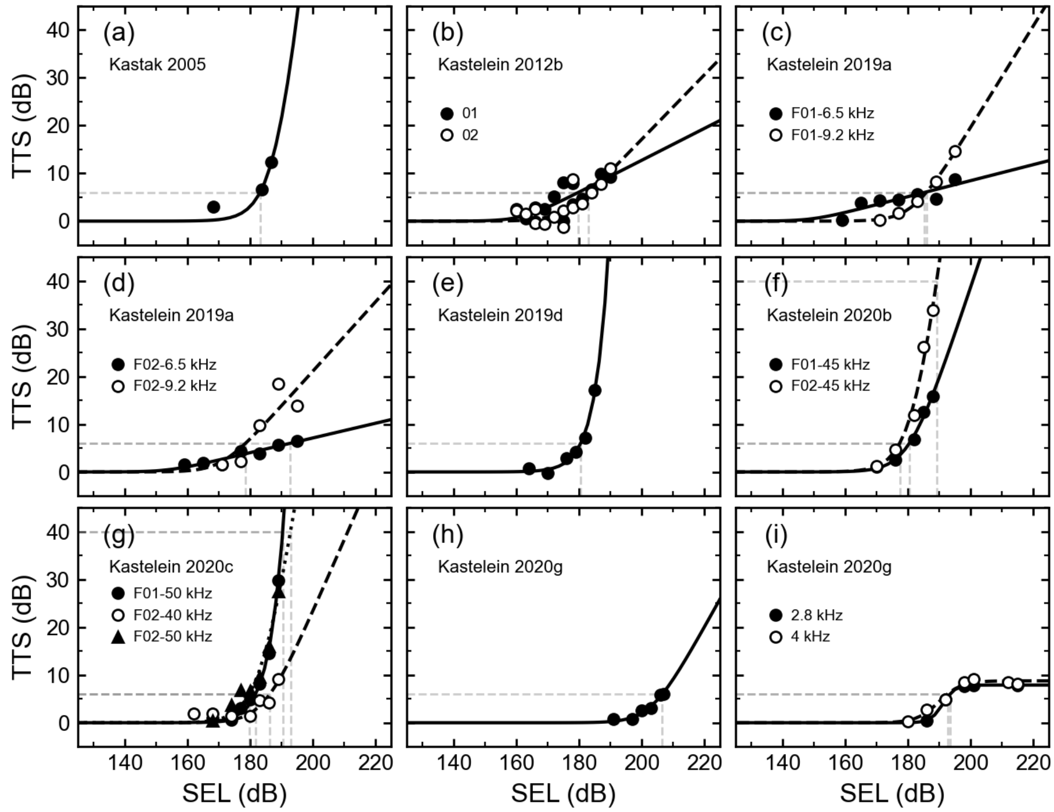

Figure A.3-6. **TTS growth data for group PCW obtained using behavioral methods. Growth curves were obtained by fitting Eq. (4) or (5) to the TTS data as a function of SEL. Onset TTS was defined as the SEL value from the fitted curve at TTS = 6 dB, for only those datasets that bracketed 6 dB of TTS. Onset INJ was defined as the SEL value from the fitted curve at a TTS = 40 dB, for only those datasets with maximum TTS > 20 dB. Solid lines are fit to the filled circles, dashed lines are fit to the open circles, and the dotted line is fit to the triangles. See Table A.3-6 for explanation of the datasets in each panel. SEL units are dB re 1 μPa²s.**

Table A.3-6. Summary of group PCW TTS growth data and onset exposure levels. Only those data from which growth curves could be generated are included. TTS onset values are expressed in SEL, in dB re 1 μPa²s. Tests featured exposure to steady-state noise and behavioral threshold measurements. "Panel" refers to corresponding sub-panel plot within Figure A.3-5.

Group	Species	Study	Subject	Exp. Freq. (kHz)	Hear. Freq. (kHz)	Min TTS (dB)	Max TTS (dB)	TTS onset (dB SEL)	TTS growth rate (dB/dB)	INJ onset (dB SEL)	INJ-TTS offset (dB)	Notes	Panel
PCW	*Phoca vitulina*	Kastak 2005	Sprouts	2.5	2.5	3	12	183	6.5	—	—	—	(a)
		Kastelein 2012b	Seal 01	4	4	0	9.9	180	0.33	—	—	—	(b)
			Seal 02	4	4	0	11	183**	0.68	—	—	TTS measured 12-16 min post-exposure	(b)
		Kastelein 2019a	F01	6.5	6.5	0.3	8.8	185**	0.17	—	—	TTS measured 12-16 min post-exposure	(c)
				6.5	9.2	0.3	15	186**	1.1	—	—	TTS measured 12-16 min post-exposure	(c)
			F02	6.5	6.5	1.5	6.5	193**	0.15	—	—	Lower TTS onset at 9.2 kHz	(d)
				6.5	9.2	1.6	18	178	0.73	—	—	—	(d)
		Kastelein 2019d	F01	16	22.4	0	17	181	1.1×10^{4}	—	—	—	(e)
		Kastelein 2020b	F01	32	45	1.1	16	180**	2	—	—	TTS measured 12-16 min post-exposure	(f)
			F02	32	45	1.2	34	177	5.5	189	12	—	(f)

Table A.3-6. (cont.)

Group	Species	Study	Subject	Exp. Freq. (kHz)	Hear. Freq. (kHz)	Min TTS (dB)	Max TTS (dB)	TTS onset (dB SEL)	TTS growth rate (dB/dB)	INJ onset (dB SEL)	INJ-TTS offset (dB)	Notes	Panel
PCW	*Phoca vitulina*	Kastelein 2020c	F01	40	50	0.6	30	182**	43	190	8.6	TTS measured 12-16 min post-exposure	(g)
			F02	40	40	1.4	9.2	186**	1.5	—	—	Lower TTS onset at 50 kHz	(g)
				40	50	0.5	28	180	4.2	193	13	—	(g)
		Kastelein 2020g	F02	1	1.4	0.7	6.1	207*	1.2	—	—	—	(h)
				2	2.8	0.5	7.9	193**	—	—	—	Lower TTS onset at 4 kHz	(i)
				2	4	0.2	9.1	193*	—	—	—	—	(i)

* SELs not used during exposure function fitting process.

** Data excluded from mean onset TTS calculation. Reasons for exclusion include: (i) another data set resulted in a lower onset TTS at the same frequency, (ii) the data set featured a duty cycle less than 100%, (iii) TTS values were measured at times significantly larger than 4 min, (iv) a lower TTS onset was found at a different hearing test frequency (also see Notes).

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APPENDIX B: RESEARCH RECOMMENDATIONS FOR IMPROVED CRITERIA

In compiling, interpreting, and synthesizing the scientific literature to produce criteria for this Updated Technical Guidance, it is evident that additional data would be useful for future iterations of this document, since many data gaps still exist (Table B1). The need for the Updated Technical Guidance to identify critical data gaps was also recommended during the initial peer review and public comment period.

Table B1: Summary of currently available marine mammal data.

Hearing Group	Audiogram Data/Number of Species+	TTS Data/Number of Species	Sound Sources for TTS Studies
UNDERWATER			
LF Cetaceans	Predictive modeling*/2 species	None/0 species	None
HF Cetaceans	Behavioral/7 species	Behavioral/2 species	Octave-band noise; Tones; Mid-frequency sonar; Explosion simulator; Watergun; Airgun
VHF Cetaceans	Behavioral/2 species	Behavioral/1 species	Tones, Mid-frequency sonar; Impact pile driver; Artificial Add; Airgun
PW Pinnipeds	Behavioral/7 species	Behavioral/5 species	Octave-band noise; Impact pile driver; Airgun
OW Pinnipeds	Behavioral/3 species	Behavioral/1 species	Octave-band noise; Arc-gap transducer
IN-AIR			
PA Pinnipeds	Behavior/3	Behavioral/1	Octave-band noise
OA Pinnipeds	Behavior/3	Behavioral/1	Octave-band noise

+ This column refers specifically to data to derive the composite audiograms presented in the Updated Technical Guidance.

* NMFS is aware that the National Marine Mammal Foundation successfully collected preliminary hearing data on two minke whales during their third field season (2023) in Norway. These data have implications for not only the generalized hearing range for low-frequency cetaceans but also on their weighting function. However, at this time, no official results have been published. Furthermore, a fourth field season (2024) is proposed, where more data will likely be collected. Thus, it is premature for us to propose any changes to our current Updated Technical Guidance. However, mysticete hearing data is identified as a special circumstance that could merit re-evaluating the acoustic criteria in this document. Therefore, we anticipate that once the data from both field seasons are published, it will likely necessitate updating this document (i.e., likely after the data gathered in the summer 2024 field season and associated analysis are published).

Below is a list of research recommendations that NMFS believes would help address current data gaps. Some of these areas of recommended research have been previously identified in other publications/reports (e.g., NRC 1994; NRC 2000; Southall et al. 2007; Southall et al. 2009; Hawkins et al. 2014;[36] Houser and Moore 2014; Lucke et al. 2014; Popper et al. 2014;[37] Williams

[36] Although, Hawkins et al. 2014 identifies research gaps for fishes and invertebrates, many of the research recommendations can also be considered for other species, like marine mammals.

[37] Although Popper et al. 2014 identifies research gaps for fishes and sea turtles, many of the research recommendations can also be considered for other species, like marine mammals.

et al. 2014; Erbe et al. 2016; Lucke et al. 2016a; Popper et al. 2019[38]; Southall et al. 2019). Many of these recommendations are similar to what was provided in the NMFS 2018 Revised Technical Guidance (NMFS 2018). However, they have been updated where appropriate with new literature.

Note: Just because there may not be enough information to allow for quantifiable modifications to criteria associated with many of these recommendations, does not mean these recommendations cannot be incorporated as qualitative considerations within the comprehensive effects analysis.

I. SUMMARY OF RESEARCH RECOMMENDATIONS

1.1 LOW-FREQUENCY CETACEAN HEARING

As previously stated, direct measurements of LF cetacean hearing are lacking. Therefore, hearing predictions for these species are based on other methods (e.g., anatomical studies, predictive models, vocalizations, taxonomy, and behavioral responses to sound). Thus, additional data[39] collected would be extremely valuable to furthering the understanding of hearing ability within this hearing group and validating other methods for approximating hearing ability. For example, data (e.g., anatomical, auditory evoked potential (AEP) hearing thresholds) collected on either stranded or animals associated with subsistence hunts (e.g., Waugh et al. 2023) would be extremely useful in confirming current predictions of LF cetacean hearing ability and would allow for the development of more accurate auditory weighting functions (e.g., Do species that vocalize at ultra-low frequencies, like blue and fin whales, have dramatically different hearing abilities than other mysticete species?). Until direct measurements can be made, predictive models based on anatomical data will be the primary means of approximating hearing abilities, with validation remaining a critical component of any modeling exercise (e.g., Cranford and Krysl 2014).

In 2018, The Subcommittee on Ocean Science and Technology (SOST) Interagency Working Group on Ocean Sound and Marine Life issued a call on the topic of the development of audiograms for mysticetes. Three projects that covered a variety of methods were funded to increase the chance of success in obtaining data to address the need topic:

1. Collection of auditory evoked potential hearing thresholds in minke whales (*Balaenoptera acutorostrata*)[40]
    - Principal Investigator: Dorian Houser (National Marine Mammal Foundation)
    - The objective of this project is to collect AEP hearing thresholds for one mysticete species, the minke whale. This method involves measuring small voltages that the brain and auditory nervous system generate in response to sound. The minke AEP hearing thresholds will provide the first direct measurement of hearing in a mysticete, which will contribute to the development of a mysticete audiogram.

2. Towards a mysticete audiogram using humpback whales' behavioral response thresholds

[38] Although Popper et al. 2019 identifies research gaps for fishes, many of the research recommendations can also be considered for other species, like marine mammals.
[39] Data should be collected under appropriate permits or authorizations.

[40] NMFS is aware that the National Marine Mammal Foundation successfully collected preliminary hearing data on two minke whales during their third field season (2023) in Norway. These data have implications for not only the generalized hearing range for low-frequency cetaceans but also on their weighting function. However, at this time, no official results have been published. Furthermore, a fourth field season (2024) is proposed, where more data will likely be collected. Thus, it is premature for us to propose any changes to our current Updated Technical Guidance. However, mysticete hearing data is identified as a special circumstance that could merit re-evaluating the acoustic criteria in this document. Therefore, we anticipate that once the data from both field seasons are published, it will likely necessitate updating this document (i.e., likely after the data gathered in the summer 2024 field season and associated analysis are published).

   - Principal Investigators: Rebecca Dunlop and Michael Noad (The University of Queensland)
   - The objective of this project is to use behavioral response experiments as a proxy for audiometric measurements to estimate hearing sensitivity in humpback whales. The researchers will play a range of tones to migrating humpback whales at frequencies across their expected hearing range and will observe their behavioral response to develop an audiogram.

3. Investigating bone-conduction as a pathway for mysticete hearing
   - Principal Investigators: Ted Cranford (San Diego State University) and Petr Krysl (University of California San Diego)
   - The objective of this project is to investigate whether bone conduction is a valid pathway for hearing in mysticetes as previously reported by this team. The investigators will use a combination of finite element model simulations and two interdependent lab experiments designed to measure the transmission of sound vibrations from the water into the skull and hearing apparatus of a gray whale (stranded specimen).

Data collected with these projects will aid in informing in future iterations of the Technical Guidance.

1.2 Hearing Diversity Among Species and Auditory Pathways

A better understanding of hearing diversity among species within a hearing group is also needed (e.g., Mooney et al. 2014) to comprehend how representative certain species (e.g., bottlenose dolphins, harbor porpoise, harbor seals) are of their hearing group as a whole. For example, are there certain species more susceptible to hearing loss from sound (i.e., all members of VHF cetaceans), or are there additional delineations needed among the current hearing groups (e.g., deep diving species, separating certain species within LF or HF cetaceans or PW pinnipeds into their own hearing groups as suggested by Southall et al. 2019, etc.)? Having more data from species within a hearing group would also help identify if additional hearing groups are needed. This is especially the case for VHF cetaceans where data are only available from six individuals of two species and those individuals have a lower hearing threshold compared to all other hearing groups.

Additionally, having a more complete understanding of how sound enters the heads/bodies of marine mammals and its implication on hearing and impacts of noise among various species is another area of importance (e.g., bone conduction mechanism in mysticetes: Cranford and Krysl 2015; previously undescribed acoustic pathways in odontocetes: Cranford et al. 2008; Cranford et al. 2010; filtering/amplification of transmission pathway: Cranford and Krysl 2012; directional hearing: Renaud and Popper 1975; Au and Moore 1984; Kastelein et al. 2005b).

1.3 Representativeness of Captive Individuals

Data from Castellote et al. (2014), from free-ranging belugas in Alaska, indicate that of the seven healthy individuals tested (3 females/4 males; 1 subadult/6 adults), all had hearing abilities “similar to those of belugas measured in zoological settings.” In a follow-up publication, Mooney et al. (2018) obtained audiograms from 26 more belugas in Alaska, including seven animals from Castellote et al. (2014), and reported “ thresholds of sensitive individuals were comparable to those of some odontocetes that were measured in controlled laboratory conditions and were without hearing loss.”

Similarly, data from Ruser et al. (2017) reported that harbor porpoise live-stranded (15 individuals both males and females; subadults and adults) and wild individuals incidentally caught in pound nets (12 both males and females; subadult and adults) had “the shape of the hearing curve is generally similar to previously published results from behavioral trials.” Thus, from these studies, it appears that for baseline hearing measurements, captive individuals may be appropriate surrogates for free-ranging animals. Additionally, Mulsow et al. (2011b) measured aerial hearing abilities of seven stranded California sea lions and found a high degree of intersubject variability but that high-frequency hearing limits were consistent with previously tested captive individuals. However, these are currently the only studies of their kind. Finally, Lucke et al. (2016b) compared aerial hearing in captive and free-ranging harbor seals and found "relatively small differences [aerial hearing thresholds] between the animals in both test settings (zoo and the wild)."

More research is needed to examine if this trend is applicable to other species (Lucke et al. 2016a).

1.3.1 Impacts of Age on Hearing

Hearing loss can result from a variety of factors beyond anthropogenic noise, including exposure to ototoxic compounds (chemicals poisonous to auditory structures), disease and infection, and heredity, as well as a natural part of aging (Corso 1959; Kearns 1977; WGSUA 1988; Yost 2007). High-frequency hearing loss, presumably a normal process of aging that occurs in humans and other terrestrial mammals, has also been demonstrated in captive cetaceans (Ridgway and Carder 1997; Yuen et al. 2005; Finneran et al. 2005b; Houser and Finneran 2006; Finneran et al. 2007b; Schlundt et al. 2011) and in stranded individuals (Mann et al. 2010). Thus, the potential impacts of age on hearing can be a concern when extrapolating from older to younger individuals.

Few studies have examined this phenomenon in marine mammals, particularly in terms of the potential impact of aging on hearing ability and TSs:

- Houser and Finneran (2006) conducted a comprehensive study of the hearing sensitivity of the U.S. Navy bottlenose dolphin population (i.e., tested 42 individuals from age four to 47 years; 28 males/14 females). They found that high-frequency hearing loss typically began between the ages of 20 and 30 years. However, the frequencies where this species is most susceptible to noise-induced hearing loss (i.e., 10 to 30 kHz) are the frequencies where the lowest variability exists in mean thresholds between individuals of different ages.

- Houser et al. (2008) measured hearing abilities of 13 Pacific bottlenose dolphins, ranging in age from 1.5 to 18 years. The authors' reported that "Variability in the range of hearing and age-related reductions in hearing sensitivity and range of hearing were consistent with those observed in Atlantic bottlenose dolphins."

- Mulsow et al. (2014) examined aerial hearing thresholds for 16 captive sea lions, from age one to 26 years, and found that only the two 26-year old individuals had hearing classified as "aberrant" compared to other individuals (i.e., high-frequency hearing loss), which were deemed to have similar hearing abilities to previously measured individuals.

- Additionally, for harbor seals, similar exposure levels associated with TTS onset were found in Kastelein et al. 2012a for individuals of four to five years of age compared to that used in Kastak et al. 2005, which was 14 years old and for belugas in Popov et al. 2014 for an individual of 2 years of age compared to those used in Schlundt et al. 2000, which were 20 to 22 years old or 29 to 31 years old.

From these limited data, it appears that age may not be a significant complicating factor, in terms of assessing TSs for animals of different ages. Nevertheless, additional data are needed to confirm if these data are representative for all species (Lucke et al. 2016a).

1.4 Additional TTS Measurements with More Species and/or Individuals

Currently, TTS measurements only exist for four species of cetaceans (bottlenose dolphins, belugas, harbor porpoises, and Yangtze finless porpoise) and six species of pinnipeds (Northern elephant seal, harbor seal, ringed seal, spotted seal, bearded seal, and California sea lion). Additionally, the existing marine mammal TTS measurements are from a limited number of individuals within these species. Having more data from a broader range of species and individuals would be useful to confirm how representative current individuals are of their species and/or entire hearing groups (Lucke et al. 2016a). For example, TTS onset criteria for harbor porpoise (VHF cetacean) are much lower compared to other odontocetes (HF cetaceans), and it would be useful to know if all VHF cetaceans share these lower TTS onset criteria or if harbor porpoises are the exception.

Finally, cetaceans are often used as surrogates for pinnipeds when no direct data exist. Having more information on the appropriateness of using cetaceans as surrogates for pinnipeds would be useful (i.e., Is there another mammalian group more appropriate?).

1.5 Sound Exposure to More Realistic Scenarios

Most marine mammal TTS measurements are for individuals exposed to a limited number of sound sources (i.e., mostly tones and octave-band noise[41]) in primarily[42] laboratory settings. Measurements from exposure to actual sound sources (opposed to tones or octave-band noise) under more realistic exposure conditions (e.g., more realistic exposure durations and/or scenarios, including multiple pulses/pile strikes and at frequencies below 1 kHz where most anthropogenic noise occurs) are needed.

1.5.1 Frequency and Duration of Exposure

In addition to received level, NMFS recognizes that other factors, such as frequency and duration of exposure, are also important to consider within the context of AUD INJ onset criteria (Table B2). However, there are not enough data to establish numerical criteria based on these added factors (e.g., alternatives to the EEH for accumulated exposure), beyond what has already been included in this document, in terms of marine mammal auditory weighting functions and SEL_{24h} criteria. When more data become available, it may be possible to incorporate these factors into quantitative assessments.

Further, it has been demonstrated that exposure to lower-frequency broadband sounds has the potential to cause TSs at higher frequencies (e.g., Lucke et al. 2009; Kastelein et al. 2015a; Kastelein et al. 2016). The consideration of duty cycle (i.e., energy per unit time) is another important consideration in the context of exposure duration (e.g., Kastelein et al. 2015b). Having a better understanding of these phenomena would be helpful.

1.5.2 Multiple Sources

Further, a better understanding of the effects of multiple sources and multiple activities on TS, as well as impacts from long-term exposure is needed. Studies on terrestrial mammals indicate that exposure scenarios from complex exposures (i.e., those involving multiple types of sound sources) result in more complicated patterns of NIHL (e.g., Ahroon et al. 1993). Recently Guan et al. 2022 and Guan and Brookens 2023 indicated that there is a need to conduct TTS

[41] More recent studies (e.g., Lucke et al. 2009; Mooney et al. 2009b; Kastelein et al. 2014a; Kastelein et al. 2014b; Kastelein et al. 2015a; Kastelein et al. 2015b; Finneran et al. 2015; Kastelein et al. 2016; Kastelein et al. 2017b; Kastelein et al. 2017c; Kastelein et al. 2018; Kastelein et al. 2020f; Sills et al. 2020b) have used exposures from more realistic sources, like airguns, impact pile drivers, or tactical sonar.

[42] Pacini et al. 2017 reported NIHL in stranded rough-toothed and spinner dolphins exposed to dynamite fishing.

measurements on exposures to more complex sounds (e.g., multiple sounds, including those with both impulsive and non-impulsive components).

1.5.3 Possible Protective Mechanisms

Nachtigall and Supin (2013) reported that a false killer whale was able to reduce its hearing sensitivity (i.e., conditioned dampening of hearing) when a loud sound was preceded by a warning signal. Nachtigall and Supin (2014) reported a similar finding in a bottlenose dolphin, a beluga (Nachtigall et al. 2016a), and in harbor porpoises (Nacthigall et al. 2016b). Further studies showed that conditioning is associated with the frequency of the warning signal (Nachtigall and Supin 2015), as well as if an animal is able to anticipate when a loud sound is expected to occur after a warning signal (Nachtigall et al. 2016c).

Table B2: Additional factors for consideration (frequency and duration of exposure) in association with AUD INJ onset criteria.

Factor	General Trends
Frequency	1) Growth of TS: Growth rates of TS (dB of TTS/dB noise) are higher for frequencies where hearing is more sensitive (e.g., Finneran and Schlundt 2010; Finneran and Schlundt 2013; Kastelein et al. 2014a; Kastelein et al. 2015b)
Duration	1) Violation of : Non-impulsive, intermittent exposures require higher SEL_{24h} to induce a TS compared to continuous exposures of the same duration (e.g., Mooney et al. 2009a; Finneran et al. 2010b; Kastelein et al. 2014a) 2) Violation of EEH: Exposures of longer duration and lower levels induce a TTS at a lower level than those exposures of higher level (below the critical level) and shorter duration with the same SEL_{24h} (e.g., Kastak et al. 2005; Kastak et al. 2007; Mooney et al. 2009b; Finneran et al. 2010a; Kastelein et al. 2012a; Kastelein et al. 2012b) 3) Recovery from a TS: With the same SEL_{24h}, longer exposures require longer durations to recover (e.g., Mooney et al. 2009b; Finneran et al. 2010a) 4) Recovery from a TS: Intermittent exposures recover faster compared to continuous exposures of the same duration (e.g., Finneran et al. 2010b; Kastelein et al. 2014a; Kastelein et al. 2015b)
Cumulative Exposure	1) Animals may be exposed to multiple sound sources and stressors, beyond acoustics, during an activity, with the possibility of additive or synergistic effects (e.g., Sih et al. 2004; Rohr et al. 2006; Chen et al. 2007; Lucke et al. 2016a; NRC 2016)

Additionally, Finneran et al. (2015) observed two of the three dolphins in their study displayed “anticipatory” behavior (e.g., head movement) during an exposure sequence to multiple airgun shots. It is unknown if this behavior resulted in some mitigating effects of the exposure. Popov et al. (2016) investigated the impact of prolonged sound stimuli (i.e., 1500 s continuous pip successions versus 500-ms pip trains) on the beluga auditory system and found that auditory adaptation occurred during exposure (i.e., decrease in amplitude of rate following response associated with evoked potentials) at levels below which TTS onset would likely be induced. The amount of amplitude reduction depended on stimulus duration, with higher reductions occurring during prolonged stimulation. The authors also caution that adaptation will vary with sound parameters. Similarly, Kastelein et al. 2020f also believed a harbor porpoise was able to "self mitigate" exposure to repeated airgun shots. Finneran (2018) confirmed that bottlenose dolphins can "self mitigate" when warned of an upcoming exposure and that mechanism for this mitigation occurs in the cochlea or auditory nerve. More recently, Finneran et al. (2023b, 2023c) demonstrated that bottlenose dolphins can self mitigate based on the ability to learn the timing of repetitive, intermittent sounds, and increased exposure level.

In the wild, potential protective mechanisms have been observed, with synchronous surfacing associated with exposure to playbacks of tactical sonar recorded in long-finned pilot whales (Miller et al. 2012). However, it is unclear how effective this behavior is in reducing received levels (Wensveen et al. 2015).
Thus, marine mammals may have multiple means of reducing or ameliorating the effects of noise exposure. However, at this point, directly incorporating them into a comprehensive effects analysis that anticipates the likelihood of exposure ahead of an activity is difficult. More information on these mechanisms, especially associated with real-world exposure scenarios, would be useful.

1.5.4 Long-Term Consequences of Exposure

Kujawa and Liberman (2009) found that with large, but recoverable noise-induced threshold shifts (maximum 40 dB TS measured by auditory brainstem response (ABR)), sound could cause delayed cochlear nerve degeneration in mice. Further, Lin et al. (2011) reported a similar pattern of neural degeneration in guinea pigs after large but recoverable noise-induced TSs (maximum ~50 dB TS measured by ABR), which suggests a common phenomenon in all mammals. The long-term consequences of this degeneration remain unclear.

Another study reported impaired auditory cortex function (i.e., behavioral and neural discrimination of sound in the temporal domain (discriminate between pulse trains of various repetition rates)) after sound exposure in rats that displayed no impairment in hearing (Zhou and Merzenich 2012). Zheng (2012) found reorganization of the neural networks in the primary auditory cortex (i.e., tonotopic map) of adult rats exposed to low-level noise, which suggests an adaptation to living in a noisy environment (e.g., noise exposed rats performed tasks better in noisy environment compared to control rats). Heeringa and van Dijk (2014) reported firing rates in the inferior colliculus of guinea pigs had a different recovery pattern compared to ABR thresholds. Bohne et al. 2017 found that noise-exposed chinchillas demonstrated that inner ear hair cells and their support cells continue to degenerate months after exposure. Thus, it is recommended that there be additional studies to look at these potential effects in marine mammals (Tougaard et al. 2015).

Houser (2021) best described TTS as a continuum of responses: "A limited amount of evidence from terrestrial laboratory animals suggests that both neuropathic and non-neuropathic TTS are feasible, with the onset of neuropathology occurring at noise exposures well exceeding those corresponding to the onset of TTS. Given this evidence, it is probable that threshold shifts in marine mammals can occur with noise exposures that also range in magnitude and effect from fully recoverable TTS without tissue damage, through fully recoverable TTS with tissue damage, to the destruction of tissue producing PTS. In other words, TTS is a graded phenomenon that is fully recoverable at low levels but can lead to tissue damage as it becomes more extreme–not all TTS results in the destruction of tissue." Thus, the Updated Technical Guidance has adopted the approach of considering auditory injury along with PTS.

Finally, it is also important to understand how repeated exposures resulting in TTS could potentially lead to AUD INJ (e.g., Kastak et al. 2008; Wang and Ren 2012; Reichmuth et al. 2019). For example, occupational noise standards, such as those from the Occupational Safety &

Health Administration (OSHA), consider the impact of noise exposure over a lifetime of exposure (e.g., 29 CFR Part 1926 over 40 years). Similar, longer-term considerations are needed for marine mammals.

1.6 Impacts of Noise-Induced Threshold Shifts on Fitness

When considering noise-induced threshold shifts, it is important to understand that hearing is more than merely the mechanical process of the ear and neural coding of sound (detection). It also involves higher processing and integration with other stimuli (perception) (Yost 2007; Alain and Berstein 2008). Currently, more is known about the aspects of neural coding of sounds compared to the higher-level processing that occurs on an individual level.

Typically, effects of noise exposure resulting in energetic (Williams et al. 2006; Barber et al. 2010) and fitness consequences (increased mortality or decreased reproductive success) are deemed to have the potential to affect a population/stock (NRC 2005; Southall et al. 2007; SMRU Marine 2014) or as put by Gill et al. 2001 “From a conservation perspective, human disturbance of wildlife is important only if it affects survival or fecundity and hence causes a population to decline.” The number of individuals exposed and the location and duration of exposure are important factors, as well. To determine whether a TS will result in a fitness consequence requires one to consider several factors.

First, one has to consider the likelihood an individual would be exposed for a long enough duration or to a high enough level to induce a TS (e.g., realistic exposure scenarios). Richardson et al. (1995) hypothesized that “Disturbance effects are likely to cause most marine mammals to avoid any ‘zone of discomfort or nonauditory effects’ that may exist” and that “The greatest risk of immediate hearing damage might be if a powerful source were turned on suddenly at full power while a mammal was nearby.” It is uncertain how frequently individuals in the wild are experiencing situations where TSs are likely from individual sources (Richardson et al.1995; Erbe and Farmer 2000; Erbe 2002; Holt 2008; Mooney et al. 2009b).

In determining the severity of a TS, it is important to consider the magnitude of the TS, time to recovery (seconds to minutes or hours to days), the frequency range of the exposure, the frequency range of hearing and vocalization for the particular species (i.e., how animal uses sound in the frequency range of anthropogenic noise exposure; e.g., Kastelein et al. 2014b), and their overlap (e.g., spatial, temporal, and spectral). Richardson et al. (1995) noted, “To evaluate the importance of this temporary impairment, it would be necessary to consider the ways in which marine mammals use sound, and the consequences if access to this information were impaired.” Thus, exposure to an anthropogenic sound source may affect individuals and species differently (Sutherland 1996).

Finally, different degrees of hearing loss exist: ranging from slight/mild to moderate and from severe to profound (Clark 1981), with profound loss being synonymous with deafness (CDC 2004; WHO 2015). For hearing loss in humans, Miller (1974) summarized “any injury to the ear or any change in hearing threshold level that places it outside the normal range constitutes a hearing impairment. Whether a particular impairment constitutes a hearing handicap or a hearing disability can only be judged in relation to an individual’s life pattern or occupation.” This statement can translate to considering effects of hearing loss in marine mammals, as well (i.e., substituting “occupation” for “fitness”).

Simply because a hearing impairment may be possible does not necessarily mean an individual will experience a disability in terms of overall fitness consequence. However, there needs to be a better understanding of the impacts of repeated exposures. As Kight and Swaddle (2011) indicate “Perhaps the most important unanswered question in anthropogenic noise research – and in anthropogenic disturbance research, in general – is how repeated exposure over a lifetime cumulatively impacts an individual, both over the short- (e.g. condition, survival) and long- (e.g., reproductive success) term." Thus, more research is needed to understand the true consequences of noise-induced TSs (acute and chronic) to overall fitness.

1.7 Behavior of Marine Mammals Under Exposure Conditions with the Potential to Cause Hearing Impacts

Although assessing the behavioral response of marine mammals to sound is outside the scope of this document, understanding these reactions, especially in terms of exposure conditions having the potential to cause NIHL is critical to be able to predict exposure better. Understanding marine mammal responses to anthropogenic sound exposure presents a set of unique challenges, which arise from the inherent complexity of behavioral reactions. Responses can depend on numerous factors, including intrinsic, natural extrinsic (e.g., ice cover, prey distribution), or anthropogenic, as well as the interplay among factors (Archer et al. 2010). Behavioral reactions can vary not only among individuals but also within an individual, depending on previous experience with a sound source, hearing sensitivity, sex, age, reproductive status, geographic location, season, health, social behavior, or context.

Severity of behavioral responses can also vary depending on characteristics associated with the sound source (e.g., whether it is moving or stationary, number of sound sources, distance from the source) or the potential for the source and individuals to co-occur temporally and spatially (e.g., persistence or recurrence of the sound in specific areas; how close to shore, region where animals may be unable to avoid exposure, propagation characteristics that are either enhancing or reducing exposure) (Richardson et al. 1995; NRC 2003; Wartzok et al. 2004; NRC 2005; Southall et al. 2007; Bejder et al. 2009; Southall et al. 2021).

Further, not all species or individuals react identically to anthropogenic sound exposure. There may be certain species-specific behaviors (e.g., fight or flight responses; particularly behaviorally sensitive species) that make a species or individuals of that species more or less likely to react to anthropogenic sound. Having this information would be useful in improving the recommended accumulations period (i.e., 24 h) and understanding situations where individuals are more likely to be exposed to noise over longer durations and are more at risk for NIHL, either temporary or permanent.

1.8 Characteristics of Sound Associated with NIHL and Impacts of Propagation

It is known that as sound propagates through the environment various physical characteristics change (e.g., frequency content with lower frequencies typically propagating further than higher frequencies; dispersion in continental shelf or trapped waveguide propagation; increased pulse length due to reverberation or multipath propagation in shallow and deep water). Having a better understanding of the characteristics of a sound that makes it injurious (e.g., peak pressure amplitude, rise time, pulse duration, etc.; Henderson and Hamernik 1986; NIOSH 1998) and how those characteristics change under various propagation conditions would be extremely helpful in the application of appropriate criteria and be useful in supporting a better understanding as to how sounds could possess less injurious characteristics further from the source (e.g., transition range)[43].

Further, validation and/or comparison of various propagation and exposure models for a variety of sources would be useful to regulators, who with criteria that are more complex will be faced with evaluating the results from a multitude of models. This would also allow for a more complete comparison to the methodologies provided in this Updated Technical Guidance. This would allow for a determination of how precautionary these methodologies are under various scenarios and allow for potential refinement.

[43] NMFS is aware of Martin et al. 2020, which recommends the kurtosis metric to define a source's impulsiveness.

1.9 Noise-Induced Threshold Shift Growth Rates and Recovery

TS growth rate data for marine mammals are limited, with higher growth rates for frequencies where hearing is more sensitive (Finneran and Schlundt 2010; Finneran and Schlundt 2013; Kastelein et al. 2015b; Kastelein et al. 2020g; Finneran et al. 2023a; Kastelein et al. 2022a). Understanding how these trends vary with exposure to more complex sound sources (e.g., broadband impulsive sources) and among various species would be valuable.

Understanding recovery after sound exposure is also an important consideration. Currently, there is a lack of recovery data for marine mammals, especially for exposure to durations and levels expected under real-world scenarios. Thus, additional marine mammal noise-induced recovery data would be useful. A better understanding of likely exposure scenarios, including the potential for recovery, including how long after noise exposure recovery is likely to occur, could also improve the recommended baseline accumulation period.

1.10 Metrics and Terminology

Sound can be described using a variety of metrics, with some being more appropriate for certain sound types or effects compared with others (e.g., Coles et al. 1968; Hamernik et al. 2003; Madsen 2005; Davis et al. 2009; Zhu et al. 2009). A better understanding of the most appropriate metrics for establishing criteria and predicting impacts to hearing would be useful in confirming the value of providing dual metric criteria using the PK SPL and weighted SEL_{24h} metrics for impulsive sources.

As science advances, additional or more appropriate metrics may be identified and further incorporated by NMFS, such as kurtosis has been recently recommended as more appropriate metric for defining the impulsiveness of a sound (Martin et al. 2020; Müller et al. 2020; Guan et al. 2022; Guan and Brookens 2023; Zeddies et al. 2023). However, caution is recommended when comparing sound descriptions in different metrics (i.e., they are not directly comparable). Additionally, Von Benda-Beckmann et al. 2022 indicated that the applicability of the Goley et al. 2011 fitting parameter (λ) for marine mammals needs to be further investigated. Finally, the practicality of measuring and applying metrics is another important consideration.

Further, the Updated Technical Guidance’s criteria are based on the EEH, which is known to be inaccurate in some situations. Popov et al. 2014 suggested that RMS SPL multiplied by log duration better described their data than the EEH. Thus, better means of describing the interaction between SPL and duration of exposure would be valuable.

Finally, in trying to define metrics and certain terms (e.g., impulsive and non-impulsive) within the context of the Updated Technical Guidance, NMFS often found difficulties due to lack of universally accepted standards and common terminology. Within the Updated Technical Guidance, NMFS has tried to adopt terminology, definitions, symbols, and abbreviations that reflect those of the American National Standards Institute (ANSI) or more appropriately the more recent International Organization for Standardization (ISO)[44]. Thus, NMFS encourages the further development of appropriate standards for marine application.

1.11 Effective Quiet

“Effective quiet” is defined as the maximum sound pressure level that will fail to produce any significant TS in hearing despite duration of exposure and amount of accumulation (Ward et al.

[44] This version (3.0) of Updated Technical Guidance is more reflective of ISO 18405 (ISO 2017). ISO 18405 is the preferred standard because it was developed specifically for underwater acoustics, compared with standards developed for airborne acoustics that use different conventions. With the addition of in-air criteria for pinnipeds, NMFS is relying upon ISO 8000-8 (ISO 2020).

1976; Ward 1991). Effective quiet can essentially be thought of as a "safe exposure level" (i.e., risks for TS are extremely low or nonexistent) in terms of hearing loss[45] (Mills 1982; NRC 1993) and is frequency dependent (Ward et al. 1976; Mills 1982). Effective quiet is an important consideration for the onset TTS and AUD INJ criteria expressed by the weighted SEL_{24h} metric because if not taken into consideration unrealistically low levels of exposure with long enough exposure durations could accumulate to exceed current weighted SEL_{24h} criteria, when the likelihood of an actual TS is extremely low (e.g., humans exposed to continuous levels of normal speech levels throughout the day are not typically subjected to TTS from this type of exposure).

Currently, there are limited data available to define effective quiet for marine mammals. However, a study by Popov et al. 2014 on belugas exposed to half-octave noise centered at 22.5 kHz indicates that effective quiet for this exposure scenario and species might be around 154 dB. In Finneran's (2015) review of NIHL in marine mammals, effective quiet is predicted to vary by species (e.g., below 150 to 160 dB for bottlenose dolphins and belugas; below 140 dB for Yangtze finless porpoise; 124 dB for harbor porpoise; and 174 dB for California sea lions). More recently, Martin et al. 2020 suggested effective quiet be derived from daily TTS criteria for non-impulsive sources (i.e., 50 dB below TTS onset, SEL_{24}), while Pirotta et al. 2021 suggested effective quiet to be derived from human data (10 dB below TTS onset, SEL_{24} based on Ward et al. 1976[46]).

As more data become available, they would be useful in contributing to the better understanding of appropriate accumulations periods for the weighted SEL_{24h} metric and NIHL, as well as if there is potential of low-level (e.g., Copping et al. 2014; Schuster et al. 2015; Copping and Hemery 2020; Tougaard et al. 2020; Stöber and Thomsen 2021; Kulkarni and Edwards 2022), continuously operating sources (e.g., alternative energy tidal, wave, or wind turbines) to induce noise-induced hearing loss or not (i.e., below effective quiet).

1.12 Translating Biological Complexity into Practical Application

Although not a specific research recommendation, practical application of science is an important consideration. As more is learned about the potential effects of sound on marine mammals, the more complex future criteria are likely to become. Practical application always needs to be weighed against making criteria overly complicated (cost versus benefit considerations). The creation of tools to help ensure action proponents, as well as managers apply complex criteria correctly, is a critical need.

Additionally, there is always a need for basic, practical acoustic training opportunities for action proponents and managers (most acoustic classes available are for students within an academic setting and not necessarily those who deal with acoustics in a more applied manner). Having the background tools and knowledge to be able to implement the Updated Technical Guidance is critical to this document being a useful and effective tool in assessing the effects of noise on marine mammal hearing.

[45] Note: "Effective quiet" only applies to hearing loss and not to behavioral response (i.e., levels below "effective quiet" could result in behavioral responses). It also is a separate consideration from defining "quiet" areas (NMFS 2009).
[46] In reviewing Ward et al. 1976, NMFS assumes Pirotta et al. 2021 is referring to where this publication says "As a rough generalization, one can say that a 5-dB TTS_2 is produced by an 8-h exposure about 8 to 9 dB above EQ [effective quiet]…" to derive the 10 dB below TTS onset criteria they are recommending for effective quiet. Note: However, Ward et al. 1976 defines effective quiet in terms of an 8-h workday.

APPENDIX C: UPDATED TECHNICAL GUIDANCE REVIEW PROCESSES: PEER REVIEW, FEDERAL AGENCY PREVIEW, AND PUBLIC COMMENT

The Updated Technical Guidance before its finalization went through several stages of peer review and public comment.

I. PEER REVIEW PROCESS

The President's Office Management and Budget (OMB 2005) states, "Peer review is one of the important procedures used to ensure that the quality of published information meets the standards of the scientific and technical community. It is a form of deliberation involving an exchange of judgments about the appropriateness of methods and the strength of the author's inferences. Peer review involves the review of a draft product for quality by specialists in the field who were not involved in producing the draft."

The peer review of this document was conducted in accordance with NOAA's Information Quality Guidelines[47] (IQG), which were designed for "ensuring and maximizing the quality, objectivity, utility, and integrity of information disseminated by the agency" (with each of these terms defined within the IQG). Further, the IQG stipulate that "To the degree that the agency action is based on science, NOAA will use (a) the best available science and supporting studies (including peer-reviewed science and supporting studies when available), conducted in accordance with sound and objective scientific practices, and (b) data collected by accepted methods or best available methods." Under the IQG and in consistent with OMB's Final Information Quality Bulletin for Peer Review (OMB Peer Review Bulletin (OMB 2005), peer review was required before it could be disseminated by the Federal Government. OMB (2005) notes "Peer review should not be confused with public comment and other stakeholder processes. The selection of participants in a peer review is based on expertise, with due consideration of independence and conflict of interest."

The peer review of the Updated Technical Guidance consisted an independent review. Upon completion of the peer review, NMFS was required to post and respond to all peer reviewer comments received via the Peer Review Reports.

1.1 PEER REVIEW

For the peer review of this document (October/November 2022), potential qualified peer reviewers were nominated by the Marine Mammal Commission (MMC) and its Committee of Scientific Advisors on Marine Mammals. Nominated peer reviewers were those with expertise in marine mammal bioacoustics, noise-induced hearing loss or auditory injury, and/or acoustics in the marine environment.

Nominated peer reviewers were those with expertise marine mammalogy, acoustics/bioacoustics, and/or acoustics in the marine environment. Of the thirteen nominated peer reviewers, three volunteered, had no conflicts of interest, had the appropriate area of expertise,[48] and were available to complete an individual review (Table C1). The focus of the peer review was on the

[47] NOAA's Information Quality Guidelines.

[48] Reviewer credentials are posted at: https://www.noaa.gov/information-technology/update-to-20162018-technical-guidance-for-assessing-effects-of-anthropogenic-sound-on-marine-mammal

scientific/technical studies that have been applied and the manner that they have been applied in this document.

Table C1: Peer review panel.

Name	Affiliation
Dr. David Barclay	Dalhousie University
Dr. Jillian Sills	University of California Santa Cruz
Dr. Douglas Wartzok	Florida International University

1.2 CONFLICT OF INTEREST DISCLOSURE

Each peer reviewer completed a conflict of interest disclosure form. It is essential that peer reviewers not be compromised by any significant conflict of interest. For this purpose, the term "conflict of interest" means any financial or other interest which conflicts with the service of the individual because it (1) could significantly impair the individual's objectivity or (2) could create an unfair competitive advantage for any person or organization. No individual can be appointed to review information subject to the OMB Peer Review Bulletin if the individual has a conflict of interest that is relevant to the functions to be performed.

The following https://www.noaa.gov/information-technology/update-to-20162018-technical-guidance-for-assessing-effects-of-anthropogenic-sound-on-marine-mammal contains information on the peer review process including: the charge to peer reviewers, peer reviewers' names, peer reviewers' individual reports, and NMFS's response to peer reviewer reports.

1.3 CHANGES TO UPDATED TECHNICAL GUIDANCE AS A RESULT OF PEER REVIEW

Overall, most of the changes to the Updated Technical Guidance, as a result of the Peer Review, were considered minor. None of the peer reviewers identified any major issues with the Updated Technical Guidance. Peer reviewers' comments and NMFS's responses to the comments, from the peer review, can be found at: https://www.noaa.gov/sites/default/files/2023-05/ID429-FINAL-Peer-Review-Report-508_0.pdf.

1.4 CHANGES TO UPDATED TECHNICAL GUIDANCE SINCE PEER REVIEW

After the Peer Review concluded, there were minor changes made to the Updated Technical Guidance document by the Navy (December 2023). Namely, two new audiograms were published for California sea lions (Kastelein et al. 2023b) and a correction to the calculation of the offset between the TTS and AUD INJ impulsive SEL thresholds was made (i.e., rounding error) (identified during the Federal Agency Preview). These additional changes only resulted in minor changes to the thresholds and weighting functions. Thus, the Peer Reviewers were alerted to these changes prior to the public comment period and were encouraged to submit any additional comments they may have during this time.

II. FEDERAL AGENCY PREVIEW

NMFS also solicited input on the Updated Technical Guidance from other Federal agencies after the peer review (May/June 2023) but before the public comment period. NMFS contacted 17 Federal agencies to inquire if they wanted to participate in the Federal Agency Preview. Of the 17 agencies contacted, 12 asked to participate in the Federal Agency Preview (i.e., received the draft document). Six agencies provided comments on the draft document, three indicated they had no comments to provide, and three had no response (Table C2).

Table C2: Federal Agency Preview participants (in alphabetical order).

Federal Agency	Provided Comments
Bureau of Ocean Energy Management	Yes
Department of Energy	Yes
Department of Transportation	Yes
Marine Mammal Commission	Yes
National Park Service	Yes
National Science Foundation	Yes
U.S. Air Force	No response*
U.S. Army Corps of Engineers	No response*
U.S. Coast Guard	Had no comments
U.S. Fish and Wildlife Service	Had no comments
U.S. Geological Survey	Had no comments
U.S. Navy	No response*

*Federal agencies were sent multiple emails inquiring about the status of their review of the Updated Technical Guidance, but they never responded.

2.1 Changes to Updated Technical Guidance as a Result of Federal Agency Preview

Overall, most of the changes to the Updated Technical Guidance, as a result of the Federal Agency Preview, were considered minor. None of the Federal agency reviewers identified any major issues with the Updated Technical Guidance. Federal agency reviewers' comments and NMFS's responses to the comments, from the Federal Agency Preview, can be found at https://www.fisheries.noaa.gov/national/marine-mammal-protection/marine-mammal-acoustic-technical-guidance.

2.2 Changes to Updated Technical Guidance Since Federal Agency Preview

As with the Peer Review, there were minor changes made to the Updated Technical Guidance document, since the Federal Agency Preview. Namely, two new audiograms were published for California sea lions (Kastelein et al. 2023b) and a correction to the calculation of the offset between the TTS and AUD INJ impulsive SEL thresholds was made (i.e., rounding error) (identified during the Federal Agency Preview). These additional changes only resulted in minor changes to the thresholds and weighting functions. Thus, Federal Agencies were alerted to these changes prior to the public comment period and were encouraged to submit any additional comments they may have during this time.

III. Public Comment

In addition to the peer review process, NMFS recognizes the importance of feedback from action proponents/stakeholders and other members of the public. The focus of the public comment process was on both the technical aspects of the document, as well as the implementation of the science in NMFS's policy decisions under the various applicable statutes.

3.1 Public Comment Period (SECTION TBD UNTIL CLOSE OF PUBLIC COMMENT)

The 45-day public comment period was advertised via the Federal Register (NMFS 2024).

3.1.1 Summary of Public Comments Received

A total of xx comments were received from individuals, groups, organizations, and affiliations. XX of these were in the form of a letter, spreadsheet, or individual comment submitted by representatives of a group/organization/affiliation (some submitted on behalf of an organization and/or as an individual). Those commenting included: . Each provided substantive comments addressing technical aspects or issues relating to the implementation of thresholds, which were addressed in the Final Updated Technical Guidance or related Federal Register Notice.

Specific comments can be viewed on

NMFS's responses to substantive comments made during the public comment period were published in the Federal Register located on the following web page https://www.fisheries.noaa.gov/national/marine-mammal-protection/marine-mammal-acoustic-technical-guidance in conjunction with the Final Updated Technical Guidance.

3.1.2 Changes to Updated Technical Guidance as a Result of Public Comments

Public comment provided NMFS with valuable input during the development of the Updated Technical Guidance. As a result of public comments, numerous changes were incorporated in the Final Updated Technical Guidance, with the most significant being:

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APPENDIX D: GLOSSARY

95% Frequency contour percentile: Upper frequency below which 95% of total cumulative energy is contained (Charif et al. 2010).

Accumulation period: The amount of time a sound accumulates for the cumulative sound exposure level (SEL) metric.

Acoustic threshold: An acoustic threshold in this document identifies the level of sound, after which exceeded, NMFS anticipates a change in auditory sensitivity (temporary or permanent threshold shift).

Animat: A simulated marine mammal.

Anthropogenic: Originating (caused or produced by) from human activity.

Audible: Heard or capable of being heard. Audibility of sounds depends on level, frequency content, and can be reduced in the presence of other sounds (Morfey 2001)

Audiogram: A graph depicting hearing threshold (RMS SPL dB) as a function of frequency (ANSI 1995; Yost 2007) (Figure D1).

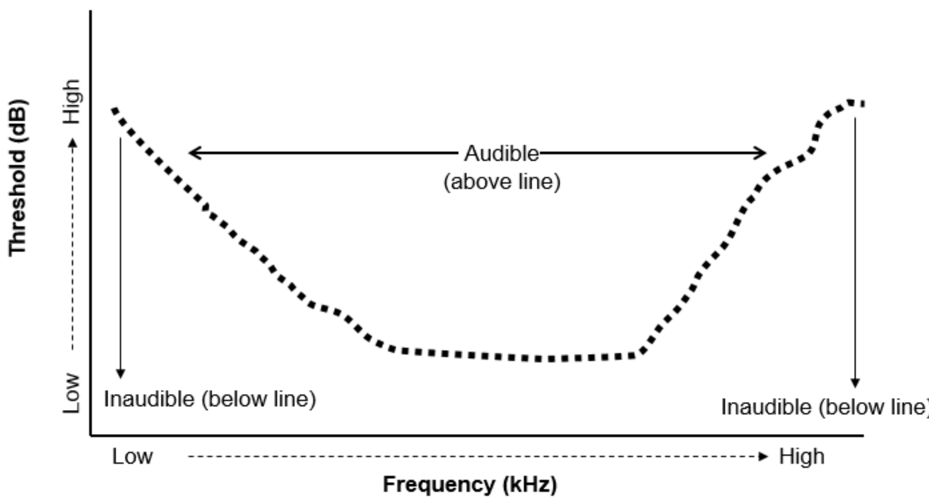

Figure D1. Example audiogram.

Auditory adaptation: Temporary decrease in hearing sensitivity occurring during the presentation of an acoustic stimulus (opposed to auditory fatigue which occurs post-stimulation) (ANSI 1995).

Auditory bulla: The ear bone in odontocetes that houses the middle ear structure (Perrin et al. 2009).

Auditory injury (AUD INJ): Damage to the inner ear that can result in destruction of tissue, such as the loss of cochlear neuron synapses or auditory neuropathy (Houser 2021; Finneran 2024). Auditory injury includes, but is not limited to PTS.

Auditory neuropathy: Auditory neuropathy is a hearing disorder in which the inner ear successfully detects sound, but has a problem with sending sound from the ear to the brain. Researchers report several causes of auditory neuropathy. In some cases, the cause may involve damage to the inner hair cells (specialized sensory cells in the inner ear that transmit information about sounds through the nervous system to the brain). In other cases, the cause may involve damage to the auditory neurons that transmit sound information from the inner hair cells to the brain (NIH 2022: https://www.nidcd.nih.gov/health/auditory-neuropathy#:~:text=Auditory%20neuropathy%20is%20a%20hearing,ages%2C%20from%20infancy%20through%20adulthood).

The long-term consequences of this degeneration (i.e., synaptopathy or hidden hearing loss) remain unclear, but it is believed to contribute to the inability to detect sounds in noise, tinnitus, or hyperacusis.

Auditory weighting function: Auditory weighting functions take into account what is known about marine mammal hearing sensitivity and susceptibility to noise-induced hearing loss and can be applied to a sound-level measurement to account for frequency-dependent hearing (i.e.,. an expression of relative loudness as perceived by the ear)(Southall et al. 2007; Southall et al. 2019; Finneran 2024). Specifically, this function represents a specified frequency-dependent characteristic of hearing sensitivity in a particular animal, by which an acoustic quantity is adjusted to reflect the importance of that frequency dependence to that animal (ISO 2017). Similar to OSHA (2013), marine mammal auditory weighting functions in this document are used to reflect the risk of noise exposure on hearing and not necessarily capture the most sensitive hearing range of every member of the hearing group.

Background noise: Total of all sources of interference in a system used for the production, detection, measurement, or recording of a signal, independent of the presence of the signal (ANSI 2013).

Band-pass filter: A filter that passes frequencies within a defined range without reducing amplitude and attenuates frequencies outside that defined range (Yost 2007).

Bandwidth: Bandwidth (Hz or kHz) is the range of frequencies over which a sound occurs or upper and lower limits of frequency band (ANSI 2005). Broadband refers to a source that produces sound over a broad range of frequencies (for example, seismic airguns), while narrowband or tonal sources produce sounds over a more narrow frequency range, typically with a spectrum having a localized a peak in amplitude (for example, sonar) (ANSI 1986; ANSI 2005).

Bone conduction: Transmission of sound to the inner ear primarily by means of mechanical vibration of the cranial bones (ANSI 1995).

Broadband: See “bandwidth”.

Cetacean: Any number of the order Cetacea of aquatic, mostly marine mammals that includes whales, dolphins, porpoises, and related forms; among other attributes they have a long tail that ends in two transverse flukes (Perrin et al. 2009).

Cochlea: Spirally coiled, tapered cavity within the temporal bone, which contains the receptor organs essential to hearing (ANSI 1995). For cetaceans, based on cochlear measurements two cochlea types have been described for echolocating odontocetes (type I and II) and one cochlea type for mysticetes (type M). Cochlea type I is found in species like the harbor porpoise and Amazon river dolphin, which produce high-frequency echolocation signals. Cochlea type II is found in species producing lower frequency echolocation signals (Ketten 1992).

Continuous sound: A sound whose sound pressure level remains above ambient sound during the observation period (ANSI 2005).

Critical level: The level at which damage switches from being primarily metabolic to more mechanical; e.g., short duration of impulse can be less than the ear's integration time, leading for the potential to damage beyond level the ear can perceive (Akay 1978).

Cumulative sound exposure level (SEL_{24h}; re: $1\mu Pa^2 s$): Level of acoustic energy accumulated over a given period of time or event (EPA 1982) or specifically, ten times the logarithm to the base ten of the ratio of a given time integral of squared instantaneous frequency-weighted sound pressure over a stated time interval or event to the reference sound exposure (ANSI 1995; ANSI 2013). Within the Updated Technical Guidance, this metric is weighted based on the document's marine mammal auditory weighting functions.

Deafness: A condition caused by a hearing loss that results in the inability to use auditory information effectively for communication or other daily activities (ANSI 1995).

Decibel (dB): One-tenth of a bel. Unit of level when the base of the logarithm is the tenth root of ten, and the quantities concerned are proportional to power (ANSI 2013).

dB/decade: This unit is typically used to describe roll-off, where a decade is a 10-times increase in frequency (roll-off can also be described as decibels per octave, where an octave is 2-times increase in frequency)

Duty cycle: On/off cycle time or proportion of time signal is active (calculated by: pulse length x repetition rate). A continuous sound has a duty cycle of 1 or 100%.

Dynamic range of auditory system: Reflects the range of the auditory system from the ability to detect a sound to the amount of sound tolerated before damage occurs (i.e., the threshold of pain minus the threshold of audibility) (Yost 2007). For the purposes of this document, the intent is relating the threshold of audibility and TTS onset levels, not the threshold of pain.

Effective quiet: The maximum sound pressure level that will fail to produce any significant threshold shift in hearing despite duration of exposure and amount of accumulation (Ward et al. 1976; Ward 1991).

Endangered Species Act (ESA): The Endangered Species Act of 1973 (16. U.S.C 1531 et. seq.) provides for the conservation of species that are endangered or threatened throughout all or a significant portion of their range, and the conservation of the ecosystems on which they depend.

NOAA's National Marine Fisheries Service and the U.S. Fish and Wildlife Service (USFWS) share responsibility for implementing the ESA.

Equal Energy Hypothesis (EEH): Assumption that sounds of equal energy produce the equal risk for hearing loss (i.e., if the cumulative energy of two sources are similar, a sound from a lower level source with a longer exposure duration may have similar risks to a shorter duration exposure from a higher level source) (Henderson et al. 1991).

Equal latency: A curve that describe the frequency-dependent relationships between sound pressure level and reaction time and are similar in shape to equal loudness contours in humans (loudness perception can be studied under the assumption that sounds of equal loudness elicit equal reaction times; e.g., Liebold and Werner 2002).

Equal-loudness contour: A curve or curves that show, as a function of frequency, the sound pressure level required to cause a given loudness for a listener having normal hearing, listening to a specified kind of sound in a specified manner (ANSI 2013).

Fitness: Survival and lifetime reproductive success of an individual.

Frequency: The number of periods occurring over a unit of time (unless otherwise stated, cycles per second or hertz) (Yost 2007).

Fundamental frequency: Frequency of the sinusoid that has the same period as the periodic quantity (Yost 2007; ANSI 2013). First harmonic of a periodic signal (Morfey 2001).

Generalized hearing range: There is no standard definition of hearing arrange currently available. Southall et al. 2007 defined upper and lower limits of the hearing range as ~60-70 dB above the hearing threshold at greatest hearing sensitivity (based on human and mammalian definition of 60 dB[49]), and Southall et al. 2019 used 60 dB to indicate audiometry data by marine mammal species.

Harmonic: A sinusoidal quantity that has a frequency which is an integral multiple of the fundamental frequency of the periodic quantity to which it is related (Yost 2007; ANSI 2013).

Hearing loss growth rates: The rate of threshold shift increase (or growth) as decibel level or exposure duration increase (expressed in dB of temporary threshold shift/dB of noise).Growth rates of threshold shifts are higher for frequencies where hearing is more sensitive (Finneran and Schlundt 2010). Typically in terrestrial mammals, the magnitude of a threshold shift increases with increasing duration or level of exposure, until it becomes asymptotic (growth rate begins to level or the upper limit of TTS; Mills et al. 1979; Clark et al. 1987; Laroche et al. 1989; Yost 2007).

Hertz (Hz): Unit of frequency corresponding to the number of cycles per second. One hertz corresponds to one cycle per second.

Hyperacusis: A rare hearing disorder of loudness perception, which has been defined as a consistently exaggerated or inappropriate responses to sounds that are neither threatening nor uncomfortably loud to a typical human (Baguley 2003).

Impulsive sound: Sound sources that produce sounds that are typically transient, brief (less than 1 second), broadband, and consist of high peak sound pressure with rapid rise time and rapid decay (ANSI 1986; NIOSH 1998; ANSI 2005). They can occur in repetition or as a single event. Examples of impulsive sound sources include explosives, seismic airguns, and impact pile drivers.

Information Quality Guidelines (IQG): Section 515 of the Treasury and General Government Appropriations Act for Fiscal Year 2001 (Public Law 106-554), directs the Office of Management and Budget (OMB) to issue government-wide guidelines that "provide policy and procedural guidance to federal agencies for ensuring and maximizing the quality, objectivity, utility, and integrity of information (including statistical information) disseminated by federal agencies." OMB issued guidelines directing each federal agency to issue its own guidelines. http://www.cio.noaa.gov/services_programs/IQ_Guidelines_011812.html

Integration time (of the ear): For a signal to be detected by the ear, it must have some critical amount of energy. The process of summing the power to generate the required energy is completed over a particular integration time. If the duration of a signal is less than the integration time required for detection, the power of the signal must be increased for it to be detected by the ear (Yost 2007).

Intermittent sound: Interrupted levels of low or no sound (NIOSH 1998) or bursts of sounds separated by silent periods (Richardson and Malme 1993). Typically, intermittent sounds have a more regular (predictable) pattern of bursts of sounds and silent periods (i.e., duty cycle).

[49] In humans, functional hearing is typically defined as frequencies at a threshold of 60 to 70 dB and below (Masterson et al. 1969; Wartzok and Ketten 1999), with normal hearing in the most sensitive hearing range considered 0 dB (i.e., 60 to 70 dB above best hearing sensitivity).

Isopleth: A line drawn through all points having the same numerical value. In the case of sound, the line has equal sound pressure or exposure levels.

Kurtosis: Statistical quantity that represents the impulsiveness ("peakedness") of the event; specifically the ratio of fourth- order central moment to the squared second-order central moment (Hamernik et al. 2003; Davis et al. 2009).

Linear interpolation: A method of constructing new data points within the range of a discrete set of known data points, with linear interpolation being a straight line between two points.

Marine Mammal Protection Act (MMPA): The Marine Mammal Protection Act (16. U.S.C. 1361 et. seq.)was enacted on October 21, 1972 and MMPA prohibits, with certain exceptions, the "take" of marine mammals in U.S. waters and by U.S. citizens on the high seas, and the importation of marine mammals and marine mammal products into the United States. NOAA's National Marine Fisheries Service and the U.S. Fish and Wildlife Service (USFWS) share responsibility for implementing the MMPA.

Masking: Obscuring of sounds of interest by interfering sounds, generally of the similar frequencies (Richardson et al. 1995).

Mean-squared error (MSE): In statistics, this measures the average of the squares of the "errors," that is, the difference between the estimator and what is estimated.

Mean-square sound pressure: Integral over a specified time interval of squared sound pressure, divided by the duration of the time interval for a specified frequency range (ISO 2017).

Multipath propagation: This phenomenon occurs whenever there is more than one propagation path between the source and receiver (i.e., direct path and paths from reflections off the surface and bottom or reflections within a surface or deep-ocean duct; Urick 1983).

Mysticete: The toothless or baleen (whalebone) whales, including the rorquals, gray whale, and right whale; the suborder of whales that includes those that bulk feed and cannot echolocate (Perrin et al. 2009).

Narrowband: See "bandwidth".

National Standard 2 (NS2): The Magnuson-Stevens Fishery Conservation and Management Act (MSA) (16 U.S.C. 1801 et. seq.) is the principal law governing marine fisheries in the U.S. and includes ten National Standards to guide fishery conservation and management. One of these standards, referred to as National Standard 2 (NS2), guides scientific integrity and states "(fishery) conservation and management measures shall be based upon the best scientific information available.

Noise-induced hearing loss: Changes in normal auditory function that occur as a consequence of noise exposure, which can be temporary or permanent (Yost 2007; NIH 2022).

Non-impulsive sound: Sound sources that produce sounds that can be broadband, narrowband or tonal, brief or prolonged, continuous or intermittent) and typically do not have a high peak sound pressure with rapid rise time that impulsive sounds do. Examples of non-impulsive sound sources include marine vessels, machinery operations/construction (e.g., drilling), certain active sonar (e.g. tactical), and vibratory pile drivers.

Octave: The interval between two sounds having a basic frequency ratio of two (Yost 2007). For example, one octave above 400 Hz is 800 Hz. One octave below 400 Hz is 200 Hz.

Odontocete: The toothed whales, including sperm and killer whales, belugas, narwhals, dolphins and porpoises; the suborder of whales including those able to echolocate (Perrin et al. 2009).

Omnidirectional: Receiving or transmitting signals in all directions (i.e., variation with direction is designed to be as small as possible).

One-third octave (base 10): The frequency ratio corresponding to a decidecade or one tenth of a decade (ISO 2017).

Otariid: The eared seals (sea lions and fur seals), which use their foreflippers for propulsion (Perrin et al. 2009).

Peak sound pressure level (PK SPL; re: 1 μPa): The greatest magnitude of the sound pressure, which can arise from a positive or negative sound pressure, during a specified time, for a specific frequency range (ISO 2017).

Perception: Perception is the translation of environmental signals to neuronal representations (Dukas 2004).

Permanent threshold shift (PTS): A permanent, irreversible increase in the threshold of audibility at a specified frequency or portion of an individual's hearing range above a previously established reference level. The amount of permanent threshold shift is customarily expressed in decibels (ANSI 1995; Yost 2007). Available data from humans and other terrestrial mammals indicate that a 40 dB threshold shift approximates PTS onset (see Ward et al. 1958, 1959; Ward 1960; Kryter et al. 1966; Miller 1974; Ahroon et al. 1996; Henderson et al. 2008).

Phocid: A family group within the pinnipeds that includes all of the "true" seals (i.e. the "earless" species). Generally used to refer to all recent pinnipeds that are more closely related to *Phoca* than to otariids or the walrus (Perrin et al. 2009).

Pinniped: Seals, sea lions and fur seals (Perrin et al. 2009).

Pulse duration: For impulsive sources, window that makes up 90% of total cumulative energy (5%-95%) (Madsen 2005)

Propagation loss (PL) Difference between source level in a specified direction and root mean square sound pressure level at specified position (ISO 2017). Note: Propagation loss is conceptually different from transmission loss (i.e., propagation loss is associated with the source level, while transmission loss is associated with a measurement at a specified distance).

Received level: The level of sound at a specified distance of interest, r, (i.e., at the animal or receiver). Note: Received level is conceptually different from source level (i.e., different quantities with different reference values).

Reference pressure: See sound pressure level.

Repetition rate: Number of pulses of a repeating signal in a specific time unit, normally measured in pulses per second. The inter-pulse interval is the inverse of this quantity.

Rise time: The time interval a signal takes to rise from 10% to 90% of its highest peak (ANSI 1986; ANSI 2013).

Roll-off: Change in weighting function amplitude (-dB) with changing frequency.

Root-mean-square sound pressure level (RMS SPL; re: 1 µPa): Ten times the logarithm to the base 10 of the ratio of the mean-square sound pressure to the specified reference value in decibels (ISO 2017).

Sensation level (dB): The pressure level of a sound above the hearing threshold for an individual or group of individuals (ANSI 1995; Yost 2007).
Sound: An alteration in pressure propagated by the action of elastic stresses in an elastic medium and that involves local compression and expansion of the medium (ISO 2017).

Sound Exposure Level (SEL; re: 1µPa^{2}s): A measure of sound level that takes into account the duration of the signal. Ten times the logarithm to the base 10 of the ratio of time-integrated squared sound pressure to the specified reference value in decibels. The time duration and frequency range should be specified (ISO 2017).

Sound Pressure Level (SPL): A measure of sound level that represents only the pressure component of sound. Ten times the logarithm to the base 10 of the ratio of time-mean-square pressure of a sound in a stated frequency band to the square of the reference pressure (1 µPa in water) (ANSI 2013).

Spatial: Of or relating to space or area.

Spectral/spectrum: Of or relating to frequency component(s) of sound. The spectrum of a function of time is a description of its resolution into components (frequency, amplitude, etc.). The spectrum level of a signal at a particular frequency is the level of that part of the signal contained within a band of unit width and centered at a particular frequency (Yost 2007).

Spectral density levels: Level of the limit, as the width of the frequency band approaches zero, of the quotient of a specified power-like quantity distributed within a frequency band, by the width of the band (ANSI 2013).

Subharmonic: Sinusoidal quantity having a frequency that is an integral submultiple of the fundamental frequency of a periodic quantity to which it is related (ANSI 2013).

Temporal: Of or relating to time.

Temporary threshold shift (TTS): A temporary, reversible increase in the threshold of audibility at a specified frequency or portion of an individual's hearing range above a previously established reference level. The amount of temporary threshold shift is customarily expressed in decibels (ANSI 1995, Yost 2007). Based on data from cetacean TTS measurements (see Southall et al. 2019 for a review), a TTS of 6 dB is considered the minimum threshold shift clearly larger than any day-to-day or session-to-session variation in a subject's normal hearing ability (Schlundt et al. 2000; Finneran et al. 2000; Finneran et al. 2002).

Threshold (of audibility): The threshold of audibility (auditory threshold) for a specified signal is the minimum effective sound pressure level of the signal that is capable of evoking an auditory sensation in a specified fraction of trials (either physiological or behavioral) (Yost 2007). It recommended that this threshold be defined as the lowest sound pressure level at which responses occur in at least 50% of ascending trials. (ANSI 2009).

Threshold shift: A change, usually an increase, in the threshold of audibility at a specified frequency or portion of an individual's hearing range above a previously established reference level. The amount of threshold shift is customarily expressed in decibels (ANSI 1995, Yost 2007).

Tinnitus: Disorder resulting in ringing of the ears or other phantom sound in the ears, which no obvious source can be found (Yost 2007).

Tone: A sound wave capable of exciting an auditory sensation having pitch. A pure tone is a sound sensation characterized by a single pitch (one frequency). A complex tone is a sound sensation characterized by more than one pitch (more than one frequency) (ANSI 2013).

Transmission Loss (TL): Reduction in a specified level between two specified points that are within an underwater acoustic field (ISO 2017). Note: Transmission loss is conceptually different from propagation loss (i.e., propagation loss is associated with the source level, while transmission loss is associated with a measurement at a specified distance).

Uncertainty: Lack of knowledge about a parameter's true value (Bogen and Spears 1987; Cohen et al. 1996).

Variability: Differences between members of the populations that affect the magnitude of risk to an individual (Bogen and Spears 1987; Cohen et al. 1996; Gedamke et al. 2011).

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